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Aerospace Technologies of the XXI Century

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Aerospace Technologies of the 21st century

"NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION"

8 – 9 June, 2000
Berlin, Germany

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Session I

NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

Dr. Vladimir G. DMITRIEV

The Russian Federation Ministry of Economics appointed Dr. Vladimir G. Dmitriev as director of TsAGI in 1998.

Dr. Vladimir Dmitriev has a distinguished aeronautical career. He worked at TsAGI for 18 years and was deeply involved in the aerodynamic design of various types of aircrafts. He received his Ph.D. degree in the Aerodynamics of Aircraft in 1978. For the last 12 years Dr. Dmitriev has been working at the Yakovlev Design Bureau, first as Deputy Chief Designer and since 1991 as First Deputy General Designer of the Yakovlev Aircrafts Design Bureau.

He has published numerous technical papers in the areas of Aerodynamics and Aircraft Design. Since 1995 V.G. Dmitriev has been the Correspondent-Fellow of the Academy of Engineering Sciences of the Russian Federation and the Full Member of the Academy of Aviation and Aeronautics. The scope of his scientific interests includes computational and experimental investigations of the layouts of subsonic passenger and transport aircraft, optimization of their parameters, control of laminar flows, trajectory tasks of flight mechanics, aircraft impact on the environment, etc. Results of his studies were used in developing such aircraft, as the An-28, An-70, An-72, An-74, Be-30, Be-32, Tu-154M, Tu-204, Il-86, Yak-42. In 1981 he was honoured with title of the State Prize Laureate for development, production and putting into service the Yak-42 passenger aircraft. During his work in the Yakovlev Design Bureau Dr. Dmitriev contributed to development, scientific-technical accompaniment, creation of the Yak-42 modifications, the Yak-42A and Yak-42D, as well as the Yak-141, first in the world supersonic VTOL (vertical takeoff and landing) ship-based fighter, and also the «Bee», remotely-controlled light aircraft. Besides his engineering work, Dr. Dmitriev has been involved in teaching as a professor at the Moscow Aviation Institute since 1980.

He states that «We would like to assure you that TsAGI will continue its efforts in integrating into the world aerospace community for the benefit of our own and for global aerospace progress.»

ADVANCED TECHNOLOGIES OF TsAGI EXPERIMENTAL RESEARCH FOR DEVELOPMENT OF MODERN AIRCRAFT

Introduction

TsAGI has a unique experimental base enabling fundamental research and applied investigations on aerodynamics, flight dynamics and strength of aerospace vehicles. TsAGI's test facilities include a complex of wind tunnels and gasdynamic research installations, static and dynamic strength labs, thermal strength and acoustic chambers, propulsion system and compressor test benches, an air-power generating complex.

Wind tunnels and gasdynamic research installations complex contains more than 100 facilities ensuring simulation of flight at velocities from 5 m/sec up to M = 20.

T-101 and T-104 full-scale subsonic wind tunnels enable testing large-scale models and full-scale aircraft with operating engines, investigating flutter, and also full-scale power plants at subsonic speeds.

TsAGI has a set of wind tunnels with approximately identical sizes of test section for testing models at various stages of flight vehicle creation.

A set of wind tunnels with test section of 0.6 m (T-112, T-113, T-114) provides range of M = 0.3÷6.0 and is intended for testing prototype models and components of flight vehicles.

A set of wind tunnels with test section of 1 m (T-108, T-116, T-117) with range of M = 0.3÷20 is intended for investigating models of different purpose flight vehicles (aircraft, rockets, space vehicles) at high hypersonic velocities.

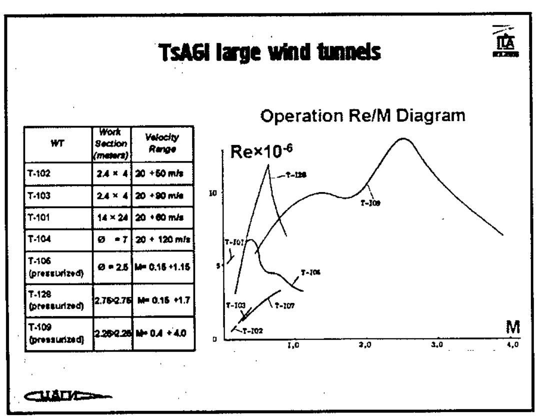
A set of large industrial wind tunnels with test section of 2.25 m up to 4 m (T-102, T-103, T-106, T-107, T-109, T-128) with range of M = 0.1÷4.0 is intended for final improvement of flight vehicle models. Some characteristics of large industrial wind tunnels are tabulated (Fig. 1).

In Fig. 1 the relations of Reynolds numbers to Mach numbers for these wind tunnels are given. The Reynolds numbers are calculated for high-aspect wing chords typical for the models tested in these wind tunnels.

The increase of Reynolds numbers up to the values similar to real ones can be provided at testing half-models and wing bays.

Apart from universal wind tunnels, which are mentioned above, there are plenty of specialised wind tunnels:

- WTs for improving power plant aerodynamics (SVS-2, TPD, T-131);



WT	Work Section (meters)	Velocity Range
T-102	2.4 × 4	20 ÷50 m/s
T-103	2.4 × 4	20 ÷90 m/s
T-101	14 × 24	20 ÷60 m/s
T-104	Ø = 7	20 ÷ 120 m/s
T-106 (pressurized)	Ø = 2.5	M= 0.15 ÷1.15
T-128 (pressurized)	2.75×2.75	M= 0.15 ÷1.7
T-109 (pressurized)	2.25×2.25	M= 0.4 ÷4.0

Figure 1

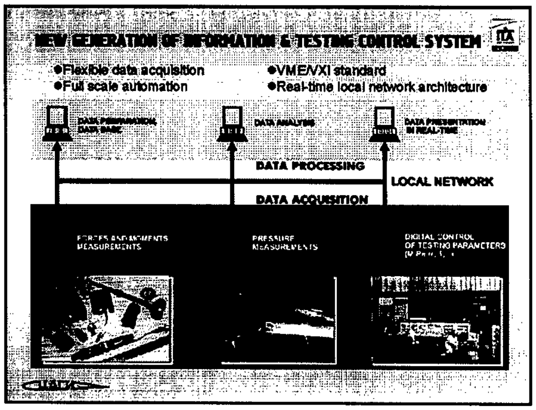


Figure 2

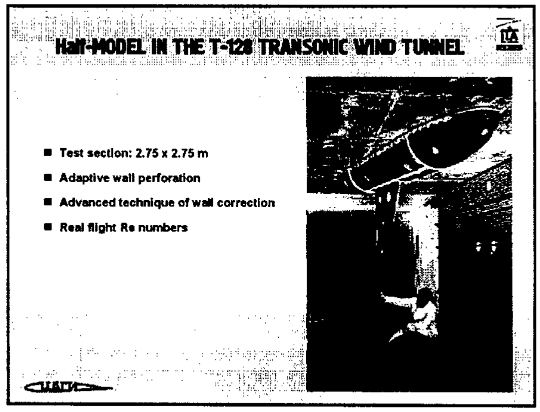


Figure 3

- Vacuum wind tunnels for investigations connected with creation of aerospace engineering objects (VAT-3, VAT-102, VAT-103, and VAT-104);
- Engine and compressor test benches ensuring investigations of hypersonic air-breathing engines and their components.

Capabilities of different test facilities will be described below.

The development of experimental base is closely connected with the development and employment of computer-measuring and control complexes. TsAGI has designed the architecture of a standard Data-Measurement-and-Control Computer System of a new-generation (EEUVS) (Fig. 2), which meets the requirements of modern experiment on accuracy, informativity and efficiency. Key features of the system are as follows: a distributed hierarchic structure of measuring and computing equipment, including those for solving real time problems (measurement, control), remote access through the local network to the system resources, operating the VME/VXI international standard for measuring equipment unification as well as using built-in and off-set computers.

TsAGI has designed unified software for complex automatization of experiment. It enables flexible arranging of the EEUVS resources, adaptation to new functions and measuring means as well as support of the system "robustness".

The EEUVS systems of a new generation are used in T-128 and T-109 wind tunnels.

Large Wind Tunnels

Transonic wind tunnel T-128 was handed over for exploitation in 1982. Aircraft models of both Russian design bureaus (Sukhoi, Mikoyan, Antonov, Tupolev, Yakovlev, Ilyshin) and foreign companies (Boeing, British Airspace, ADA, Airbus Industrie, DASA, Rockwell International, Embrauer, Design Bureaus of China) are tested in the T-128 wind tunnel.

In 1999 a new measuring system for weight experiment and a new built-in strain-gauge balance for testing passenger aircraft models at cruise flight were launched in T-128 wind tunnel. It increased the accuracy of model aerodynamic characteristic measurement. In Fig. 3 one can see the results of model retest at $M = 0.85$; $Re = 3\times10^6$. Spread in drag coefficient values for not-separated flow on the wing does not exceed 0.0001 that meets the modern requirements on aircraft development and corresponds to the level of the most advanced wind tunnels of the world.

In T-128 wind tunnel the boundary conditions on the perforated walls of the test section have been defined more exactly and also the methods of calculating boundary interference have been modified. As a result it enables more accurate determination of wall interference, which is one of the main fixed errors of wind tunnel investigations. Fig. 4 shows experimentally determined relations of lift coefficient to angle of attack, before they were corrected with account of the different values of wall perforation factor $f = 0; 2; 4; 6; 18\%$. Scatter in the corrected values is no more than ±0,02° at a non-separated flow over the wing.

T-128 wind tunnel due to its large test section, adaptive perforation and the developed methods of calculating flow boundaries influence enable testing models, including oversized half-models (Fig. 5), at Reynolds numbers close to real.

Supersonic wind tunnel T-109 (Fig. 6) has unique capabilities for different kind of aerodynamic tests, including:

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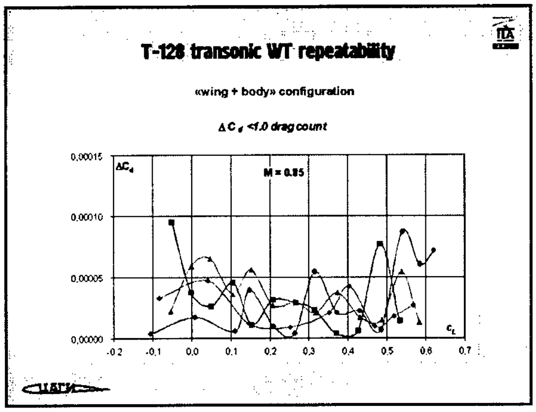
- Large Wind Tunnels
- Turbo Jet Engine Testing Wind Tunnel
- Helicopter & Spin Testing Facility
- Unsteady Aerodynamics Research Facility
- Flight Simulators
- Hypersonic Research Facility
- Hydrodynamic & Acoustic Research Facility
- Strength & Structure Research Facility

Figure 4



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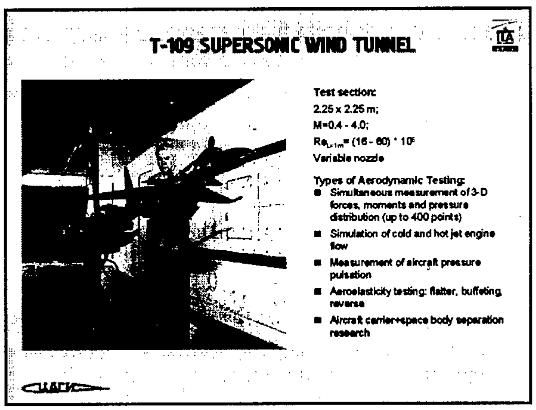


Figure 6

- Integrated experiment on measuring forces, moments and pressure distribution (400 points);
- Simulation of cold (flow rate – 250 kg/sec, P_0 = 300 atm) and hot (T = 2000°C, P_0 = 70 atm) engine jets;
- Measurement of surface pressure fluctuation (f = 0÷20 kHz);
- Investigation of Re number influence;
- Investigation of aeroelasticity (flutter, buffet, reverse);
- Full-scale simulation of flow in aircraft bays;
- Investigation of cargo-from-carrier separation processes by dropping models.

T-109 wind tunnel has modern equipment:

- Multi-channel modular measurement systems on the basis of a standard interface VXI;
- Digital systems for automatic control of wind tunnel parameters (α, β, M, Re);
- Systems for real time display of experimental data;
- Modern software;
- Adjustable nozzle;
- Support devices: tail sting, strip suspension, and half-model mounting device;
- Stream-jet facility for supplying compressed air to the model.

Test Benches for Investigating Power Plant Aerodynamics

In T-104 wind tunnel they test full-scale power plants (PP) of turbo-fan aircraft at flow rate up to 120 m/sec, angles of attack $-15° \le \alpha \le 15°$ and angles of slip $-180° \le \beta \le 180°$ (Fig. 7).

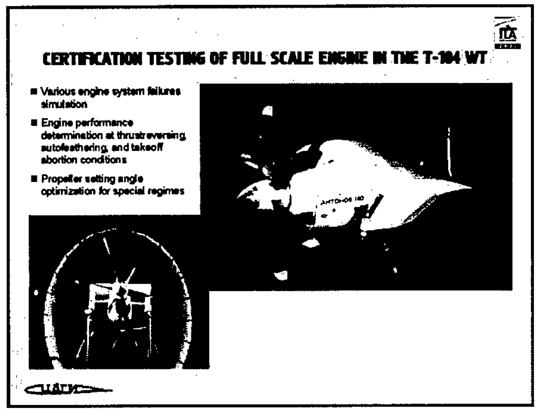


Figure 7

When testing power plants one can investigate a broad range of problems, connected with power plant exploitation at different flight modes:

- Determination of thrust characteristics, gas-dynamic parameters along the engine channel, characteristics of separate aggregates, engine stability characteristics and control system reliability;
- Set-up of engine operation modes and selection of the appropriate propeller blade incidences;
- Simulation of failures in control system and fuel-supply system;
- Determination of engine thrust performances under autorotation.

on the basis of TsAGI's wind tunnel T-104 there has been designed a new unique test bench for investigating large-scale components of turbofan engines with high and super-high by-pass ratio (air intakes, propfans, nozzles) regarding their interference and most full compliance with the requirements on aeromechanics similarity (Fig. 8).

The test bench is mounted on balance struts in the wind tunnel test section. It consists of the ducted birotative propfan and gas-generator contour. Incidences of propfan runners' blades can be varied. It is also possible to change blades. Mounting a cylindrical channel with collector inlet instead of the air intake it is possible to carry out

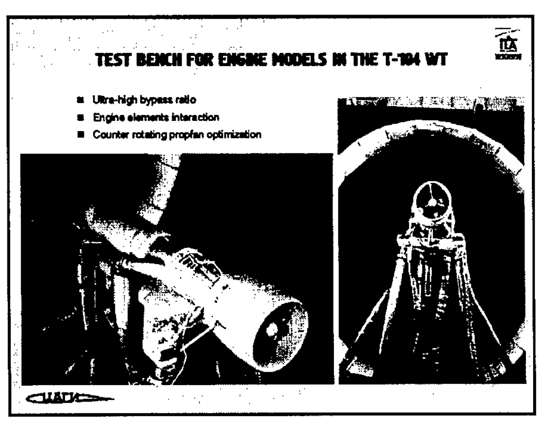


Figure 8

propfan investigations at the forward thrust mode. Changing contours of the nacelle's tail-part it is possible to simulate different ways of mechanisation for reverse thrust modes (reverse).

Prop-prop device provides rotation of runners with the same frequency. Power plant of the prop-prop device consists of two independently powered electric motors. The power is transmitted from the electric motors to two coaxial shafts, which rotate the prop-prop runners. Nominal capacity of each engine is 750 kW, maximum capacity – 800 kW. Nominal rotation frequency of each shaft is 6,000 rpm, maximum rotation frequency – 6,600 rpm.

Wind tunnel ejector regulates the by-pass ratio of the engine at a broad range. During the tests simultaneous measurements of pressure (up to 250 points) and temperature (up to 80 points), and also control of the prop-prop device, wind tunnel and ejector operation are performed in eight reference cross-sections of the flowing part .

A large-scale model (1:4) of a new-generation turbofan engine NK-93 with super-high by-pass ratio ($m \approx 14$) and birotative propfan has been successfully tested on the created test bench.

Application of Fluorescence Coatings for Pressure Measurement

Method of non-contact pressure measurement using fluorescence pressure transducers (LPD) has been developed at TsAGI. LPD is a thin coating (20 microns), which does not influence the overflow and aerodynamic characteristics. After being irradiated by the light source (impulse nitrogen laser) the coating emits luminescence light.

The LPD emission power depends on partial pressure of air oxygen, which is in linear relationship to the streamlined surface static pressure.

Transformation of the measured intensity of radiant energy in pressure field is performed by means of the "oMS" software package.

The designed measurement system was applied in the T-104 wind tunnel to determine pressure distribution along the propeller model blades. The results of the tests have proved that the LPD-coatings and measurement methods developed at TsAGI enable measurements of high quality and accuracy and are considerably superior to the methods developed by other companies.

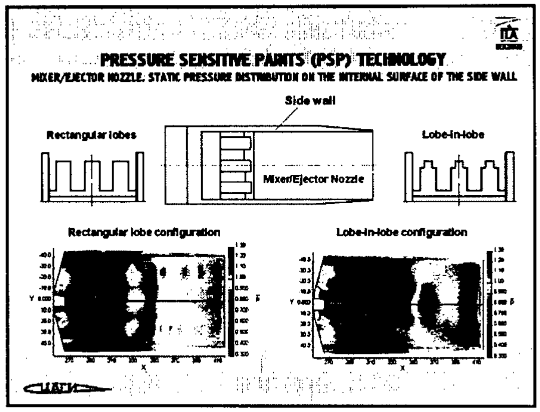


Figure 10

Fig. 9 represents the examples of static pressure distribution measurement when investigating flow over the propeller model blade SV-27 with large sabre-type bending.

Some results of using the LPD-method for investigating flow in the channel of the noise-suppressed ejector nozzle are given in Fig. 10. The measurements were performed on the internal surface of the ejector side wall at different form of corrugations.

Test Benches for Investigating Helicopter Aerodynamics and Aircraft Spin

The advance in improving aerodynamic characteristics of helicopter structures has enabled essential enhancement of the appropriate characteristics of main rotors of Russian helicopters: Mi-26, Mi-28, Mi-38, KA-50, KA-62, KA-226 etc., which were developed in close co-operation with TsAGI. When carrying out such design projects the unique helicopter facilities and full-scale wind tunnels of TsAGI have been widely used.

Fig. 11 shows helicopter test facility for large-scale models (dia up to 5 m) testing in the T-104 high-speed wind tunnel at full-scale values of Mach numbers at a whole range of speeds typical for

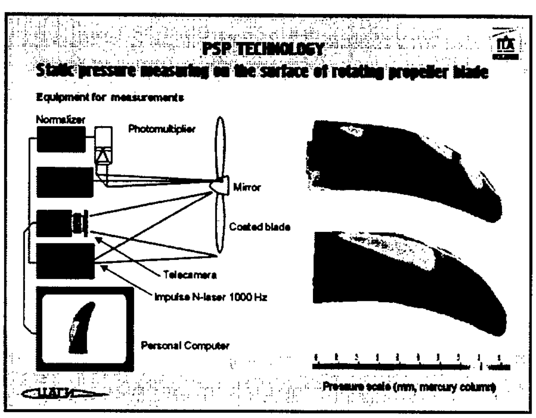


Figure 9

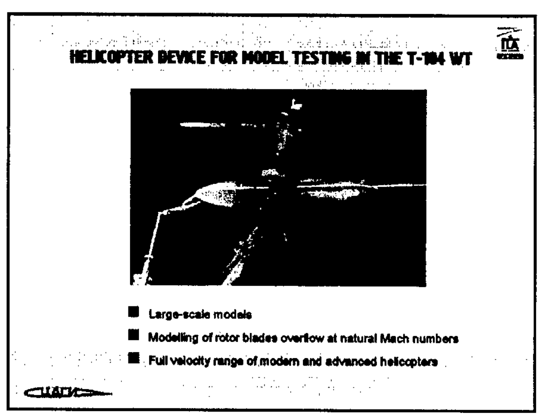


Figure 11

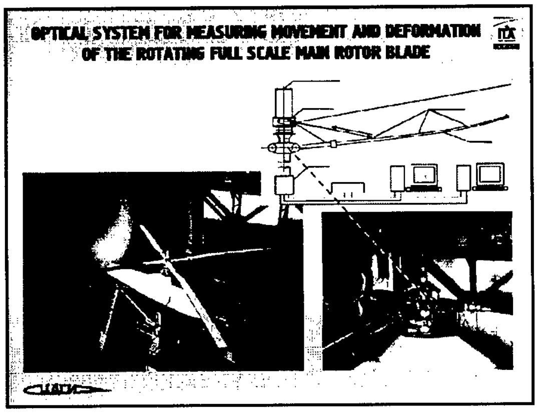


Figure 12

modern and advanced helicopters. The chart illustrates experimentally affirmed advance in the main criterions on helicopter propeller effectiveness – relative efficiency at hovering mode and maximum lift-to-drag ratio during horizontal flight in the process of increasing helicopter structure efficiency and methods of propeller aerodynamic design.

A unique optical system for measuring deformation of the blade of the rotating full-scale main rotor has been designed and is now under development at TsAGI. Fig. 12 represents the photo of the system main body mounted on the hub of the helicopter device. In this case it is equipped with full-scale blades of the KA-50 helicopter main rotor. The device is mounted in the T-101 large wind tunnel. The system operates as follows:

- The light beam of the device mounted above the rotor hub illuminates at given azimuths small reflectors placed in several sections of the blade.
- The receiving device of the system gets the reflected signals, which then subject to computer processing.

Thus, values of torsion strain and bending with respect to the end cross-section of the blade are determined in the rotation plane and blade-flapping plane.

To increase the level of aircraft flight safety TsAGI has developed an effective technology for investigating spin and stall modes and a technology for searching aerodynamic solutions ensuring "mild" stall and full absence of spin at any supercritical angles of attack and aircraft controls displacements. The basic principles of the technology are as follows:

- Experimental investigation of spin of the dynamically similar aircraft model (Fig. 13) in the T-105 vertical wind tunnel at different displacements of controls.
- Experimental investigation of different methods of aircraft spin recovery using remote control;
- Experimental investigation of full complex of aerodynamic characteristics of aircraft model (6 components of forces and moments) at a wide range of supercritical angles of attack under different model rotation speeds and controls displacements;

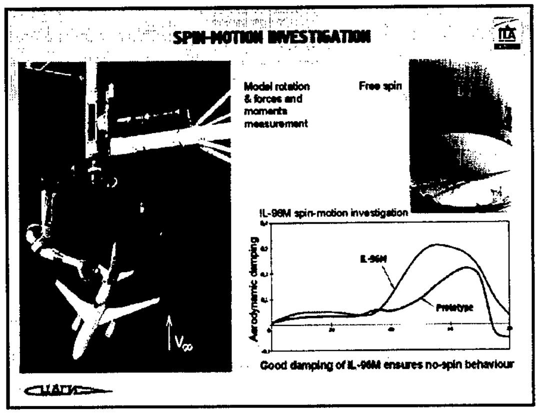


Figure 13

- Experimental investigation of non-steady aerodynamic characteristics of aircraft model in the T-103 wind tunnel using forced-oscillation method;
- Construction of mathematical model of aircraft spatial motion of at supercritical angles of attack on the basis of equations of aircraft flight dynamics at supercritical angles of attack. Aerodynamic forces and moments in these equations are determined by the results of the indicated experimental investigations.

The picture shows damping characteristics of the IL-96M aircraft rotation. By testing the IL-96M model and solving motion equations it was proved that at all combinations of controls displacements this aircraft suffers no spin. Very fast spin recovery is provided by setting the controls to the neutral position and the control wheel to the diving mode.

Experimental Base for Investigating Non-Steady Aerodynamics

TsAGI has a unique experimental base for investigation of non-steady aerodynamics (Fig. 14). The oVP-102B facility installed in the T-102 and T-103 wind tunnels provides aerodynamic damping factors (so-called complexes of rotation derivatives and non-steady aerodynamic derivatives) practically at any angles of attack and slip at Strouhal numbers close to real.

The UV-103 installation enables to investigate non-steady aerodynamic characteristics under

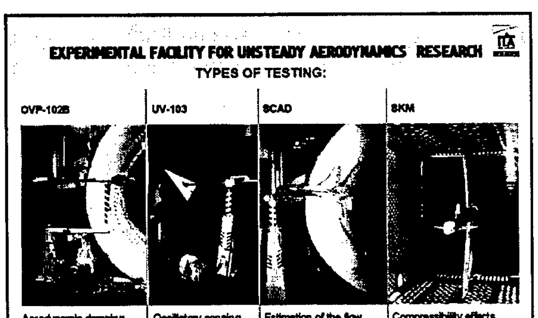


Figure 14

steady-state rotation of the model about the axis, which generally does not coincide with the flow velocity vector. These results are very important for mathematical modeling of spin and also for division of the above mentioned aerodynamic derivative complexes.

The SKM-128 installation in the T-128 wind tunnel enables to investigate non-steady aerodynamic characteristics regarding the effect of air compressibility at Mach numbers from 0.3 up to 1.5.

Installations oVP-102BA and SKAD are intended for investigating aerodynamic forces and moments at angular movements with large amplitude (for example, transition from the attached flow mode to large angles of attack, when the influence of the previous motion pattern is great and it is necessary to treat aerodynamic characteristics as dynamic systems with specific time lags). Data obtained during the experiments is necessary for developing an adequate mathematical model of aerodynamic characteristics at high angles of attack in cases when it is not enough to represent it only in view of aerodynamic coefficient derivatives. Such mathematical models enable to investigate aircraft dynamics at very complicated transient flight modes (acrobatic maneuvers such as "Pugachev's Cobra", Fig. 15).

A digital multichannel fast-response pressure-pulsation-measurement system (Fig. 16) is designed for wind tunnel investigations of non-steady processes (for example, buffeting).

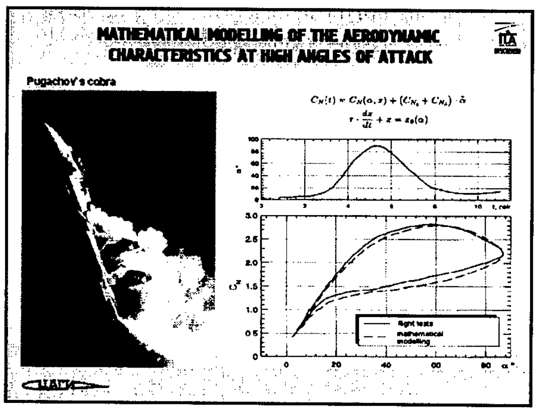


Figure 15

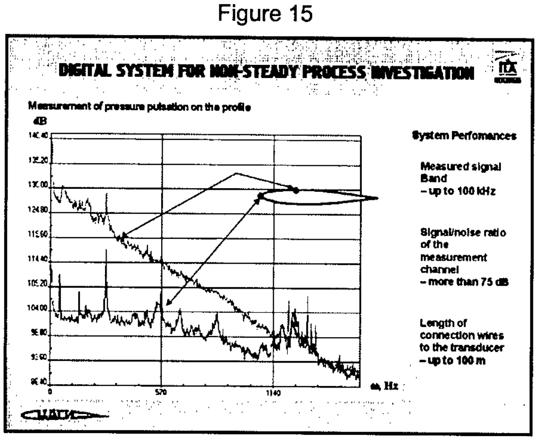


Figure 16

Flight Simulators

Experimental investigations, which include improvement of aircraft handling qualities, are a very important part of TsAGI's activities. For this purpose flight simulators are used:

- simulators of passenger aircraft and non-aerobatic airliners;
- simulators of general-purpose aircraft;
- simulators of maneuverable aircraft.

Fig. 17 shows a test bench equipped with the cockpit for investigating and experimental improvement of non-aerobatic aircraft handling qualities. The hydraulic movement gear provides 6-freedom-degree movement of the cockpit.

Investigations in the considered area accompany all stages of new manned flight vehicle development and creation, beginning with the airworthiness standards refinement. Test pilots take part in the investigations at the stages of draft-project, technical project and working project development and flight tests.

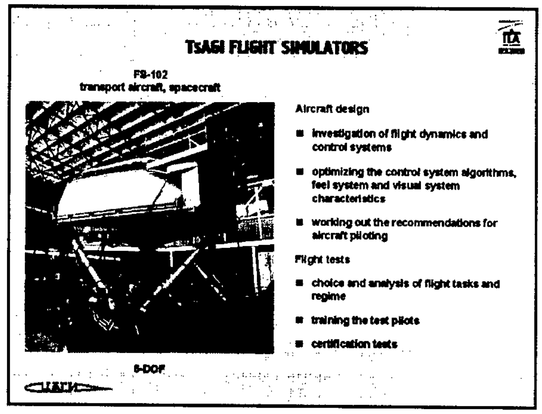


Figure 17

Problems under investigation:

Fundamental research:

- Searching new methods of increasing aircraft stability and controllability;
- Development of methods for analysing aircraft – pilot system;
- Updating of aircraft stability and controllability criterions.

Industrial and applied research:

- Investigation of the created aircraft dynamics and control systems;
- optimisation of control systems algorithms, loading characteristics of control levers and flight data display systems;
- Development of pilot guidance.

Flight test support:

- Selection of test flight modes and analysis of their results;
- Aircrew training before test flights;
- Certification tests.

The main purpose of all the above mentioned activities is as follows:

- To prepare aircraft for the first flight as much operationally developed as possible;

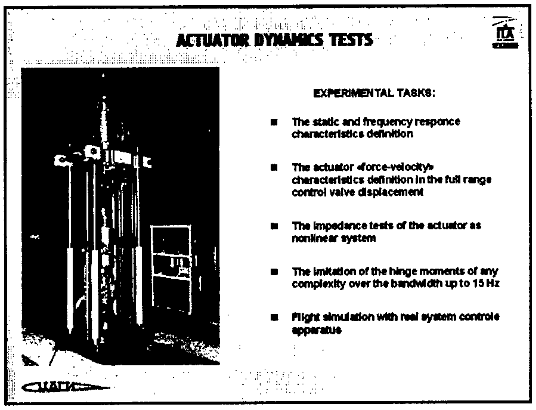


Figure 18

- To minimise flight test volumes and terms of their realisation;
- To train pilots for flight tests.

In order to be able to analyse control drives characteristics and to create their mathematical models TsAGI has designed special loading machines, which permit to simulate different kinds of loads, including hinge moments arising in flight.

Fig. 18 presents the list of problems solved using this equipment, in particular that one switched-on in the closed loop "aircraft – control system – drive-loading machine". There are also given parameters of this equipment.

Flight Parameters Measurement

TsAGI carries out investigations on developing means and methods for measuring flight parameters of different flight vehicles. It has accumulated a considerable potential in designing aerodynamic layouts of different air pressure transducers, which allow to measure all air parameters (value and direction of speed, full and static pressure) at any required angles of attack and slip at subsonic and supersonic flight speeds.

An example of such joint investigations is represented in Fig. 19: four corporations – TsAGI, Joint Stock Company "Aeropribor-Voskhod", Iliyshin Aviation Scientific Research Corporation (Russia) and "Nord-Micro" (Germany) worked together at creation of a new multifunction pitot-static tube PVD-40 and a flight parameters measuring system for trunk-route airliners. The new pitot-static tube differs from the already known ones in its carefully developed aerodynamic shape. Besides that, PVD-40 has small overall dimensions, small weight and, accordingly, low consumption of electrical power needed for heating.

PVD-40 was tested in wind tunnels and in flight tests on the IL-76MF aircraft at a whole range of possible flight modes.

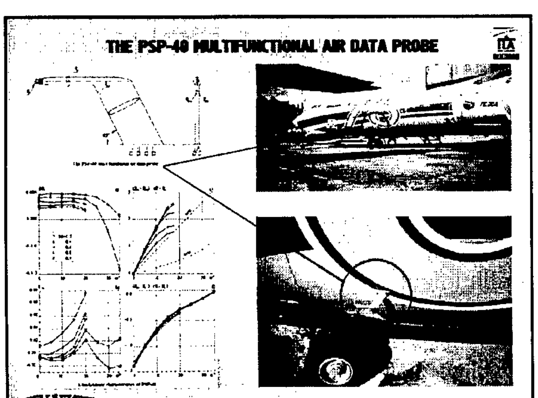


Figure 19

Experimental Base for Investigating Aerothermodynamics of Hypersonic Flight Vehicles

TsAGI's hypersonic aerodynamic test base is widely known. Among the installations one can mention the T-117 large wind tunnel, the UT-1M shock wind tunnel, the VAT-104 installation for heat protection investigations, the capabilities of which have been greatly enriched lately.

The T-117 wind tunnel now provides operational modes at Mach number from 10.5 up to 20. This wind tunnel has been modified lately in order to increase the range of the modeled parameters. There has been built a new nozzle for M = 8.25. Thus, in the wind tunnel test section a high degree of flow homogeneity (Mach number) is provided.

An automatic system of digital image processing is applied when investigating aerodynamic heating of models in the T-117 wind tunnel using the heat-indicating coating method. Fig. 20 shows isolines of equal relative values of heat flows on the upwind surface of a blunted cone at M = 10.5 and angle of attack $\alpha = 30°$.

Supersonic aerodynamic shock wind tunnel UT-1M is an effective and convenient facility, which is now widely used for investigating flow, thermoexchange and aerodynamic characteristics of bodies in gas flow. Short run duration (5÷40 ms) considerably decreases the test cost; it becomes by some orders smaller than that in continuous-operation wind tunnels. The UT-1M wind tunnel allows to receive data at a broad range of Mach numbers (M = 5, 6, 8, 10, 15.5) and Reynolds numbers $Re = (0.33 \div 80) \times 10^6$ (calculated by free flow parameters per 1 m). Diameter of nozzles in

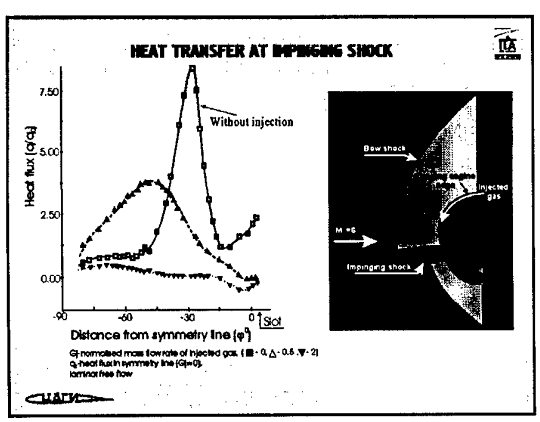


Figure 20

the exit section is D = 0.3 and 0.5 m. Air, N_2, He, CO_2 and CF_4 will be used as a working gas. The availability of ohm heater for high-pressure channel enables to apply this installation in the Ludwig scheme at Mach numbers up to 10.

The UT-1M wind tunnel has some optical systems for flow visualisation and a fast-tracking motion-picture camera. The UT-1M shock wind tunnel is supplied with devices, which permit to create a diphasic flow (gas and firm fragments). Besides that, the UT-1M shock wind tunnel is equipped with the system for supply gas to the model. This system 's surface components heat protection etc. By means of this system it was proved that using tangential injection it is possible essentially reduce heat flow in the zone of dropping shock wave – head impact wave interaction (Fig. 21).

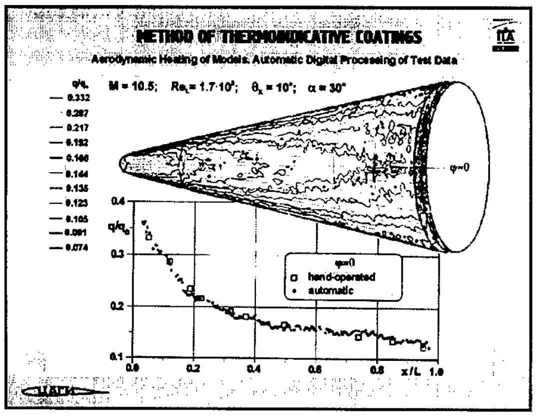


Figure 21

Complex VAT-104 is intended for atmospheric entry conditions simulation, heat protection materials and components testing under conditions, which imitate real ones. The induction heating of gas allows to avoid impurities, to ensure high stability and repeatability of modes (discrepancy is no more than 1%), capability of long-run tests (up to 1 hour) and total resource up to 104 hours. Main specifications: P_0 = 0.05÷0.6 atm, T_0 = 5,000÷8,000 K, T_w = 300÷2,500 K (temperature of the tested models surface), V_∞ = 4÷4.3 km/sec, Q_w = 50÷3×10^6 W/m^2 (heat flow to the tested model), degree of gas dissociation in the flow I – 80%, working gas – air, nitrogen, argon.

The VAT-104 installation is used for testing the model under exposure to both high-enthalpy chemically-reactive flow and mechanical load.

During heat protection components testing (except thermo-couples measurements) distribution of the surface temperature measured by the pyrometers is registered each 1÷2 seconds.

The used technique allows comparing characteristics of the material under investigation with those of the reference material (for example, plates of "Buran"). They are integrated investigations. Catalytic and radiant characteristics heat conductivity and other characteristics of the material are determined. The tests are accompanied

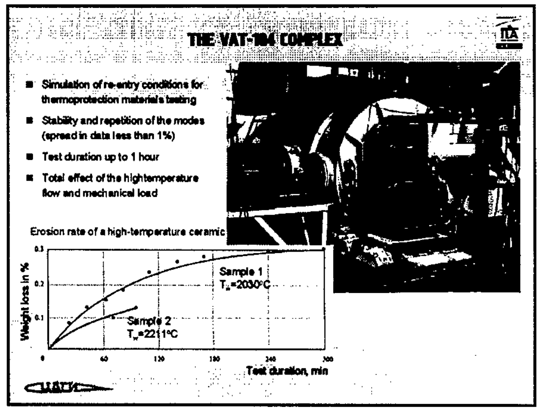


Figure 22

by numerical parametric simulation within the full Navier-Stokes equations regarding non-equilibrium chemical changes.

Fig. 22 represents the losses in weight for advanced and high-temperature ceramics as an example of investigations on the VAT-104 installation.

Hydrodynamic Test Base

The hydrodynamic experimental base enables to conduct a complete cycle of investigations for development and creation of all types of sea-based flight vehicles: amphibian aircraft, hydroplanes, wing-in-ground-effect aircraft, and hovercraft.

The test base consists of a towing tank with the following basic performances: length – 220 m, depth – 6 m, width on the water mirror – 12 m, maximum model towing speed – up to 15 m/s (Fig. 23). The towing tank is equipped with a wavemaker, underwater screens, and automatic system for test data acquiring and processing. Both "heavy" models, reproducing similar aerohydrodynamic layout and used for fixed characteristics determination, and dynamically similar models, providing the same real mass-inertia characteristics and used for determination of non-steady characteristics and stability characteristics, are applied for the tests. Models are equipped if necessary with control systems, ventilation and air supply engines.

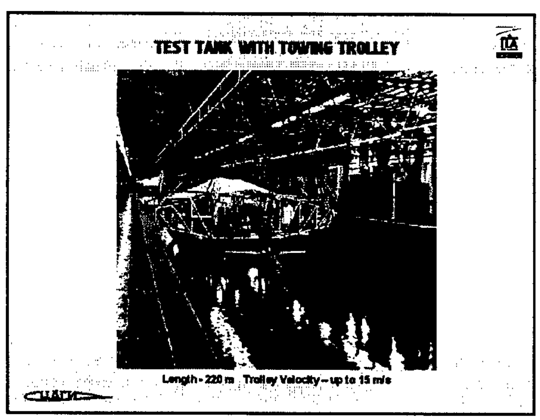


Figure 23

A considerable part of the hydrodynamic test facilities is located in the vicinity of Dubna by the Moscow Sea. Dynamically similar models are tested in real wind-wave conditions of the open pool using special boat towing.

A marine aerodrome for testing full-scale sea-based flight vehicles of take-off mass up to 10 tons is also located on the water of the Moscow Sea test base.

Floating catapults and a fast-track bench (1.8×1.8×82 m), which enables model towing with speeds up to 50 m/s and Euler number close to real, are used to simulate emergency water landing of passenger aircraft.

Acoustic Facilities

TsAGI's computational and experimental bases allow solving successfully different problems of decreasing noise of transport facilities and plants.

TsAGI's experimental base, which includes modern noise-suppressed chambers with airflow and reverberation chambers, enables thorough scientific and technical investigations of different aerodynamic noise sources, development of effective methods of noise control, determination of acoustic characteristics of sound-absorbing and sound-proofing materials and designs.

The AK-2 noise-suppressed chamber with flow (Fig. 24) is intended for investigating processes of noise formation and methods of noise reduction for low-speed and high-velocity air jets, fans, conditioning components, air ducts and different systems of supplying air to technical devices.

For investigating jet stream noise there are available three compressed air contours. Maximal air pressure in the internal contour is 220 atm, in the middle contour – 12 atm. Maximum speed of air in the external contour is up to 80 m/s. Such system of air supply enables to simulate turbofan engine jet streams expired into the vortex wake, which simulates aircraft flight conditions.

Test bench AK-11 (Fig. 25) is intended for investigating vibration-acoustic characteristics of materials, full-scale aircraft panels, full-scale objects, bays and acceptable-size models of flight vehicles in free and diffuse fields, and also in specially modeled fields very similar to real. It consists of adjacent sound-measuring chambers (one noise-suppressed camber of about 800 m^3 and two reverberation chambers each of a volume about 250 m^3). Each chamber has an insulated foundation and is mounted on special shock absorbers. The chambers have no common walls, in zones of opening between them either. All this provides a low acoustic level in each chamber and enables testing of designs with high soundtight capacity.

The conditions of the free field are provided with sound-suppressed chamber, the walls and the floor of which are lined with special sound-absorbing designs. The diffuse field, which has constant sound energy density and angular distribution of sound intensity in each point, is created in the reverberation chamber by sound waves gently fading multiple reflection from nonparallel rigid walls, floor and ceiling.

Both standard and non-standard research measurements can be carried out in the sound-suppressed and reverberation chambers.

Test bench AK-13 – a flow channel (Fig. 26) is intended for investigating characteristics (damping, frequency of set-up, impedance) of flat sound-absorbing panels in airflow at high levels of sound pressure. It consists of two reverbe-ra-tion chambers joined by the airflow channel. It is the only facility in Russia, which allows measuring

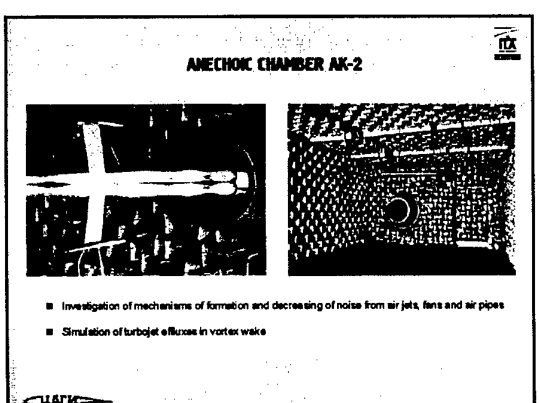


Figure 24

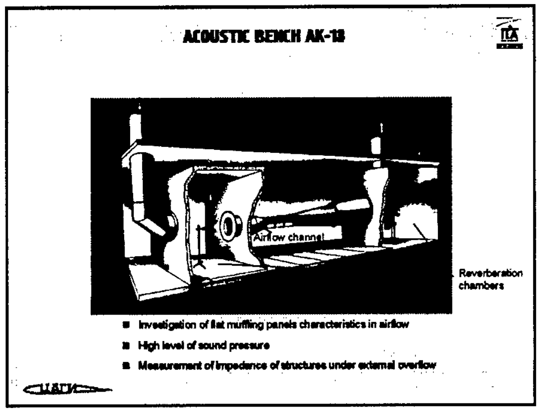


Figure 25

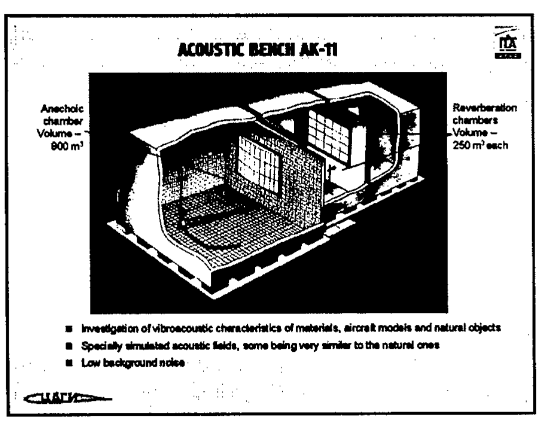


Figure 26

sound-absorbing design's impedance in conditions of external overflow.

Along with the test facilities there is a powerful software complex exercising all the advanced achievements in the sphere of noise source mathematical modeling. It enables computation of all acoustic characteristics of such noise sources as propeller, fan, air engine, turbine and gas-turbine engine jet stream; to estimate the contribution of each of these sources to the total level of a vehicle noise, to determine efficiency of different active and passive noise reduction methods, to select geometrical parameters of possible noise-reduction devices.

Experimental Base for Strength Tests

TsAGI is the center of Russian science and engineering in the area of investigation of static and thermal strength, fatigue, robustness, and also phenomena of different flight vehicles aeroelasticity. TsAGI's experimental base enables wide range of testing: from investigating strength characteristics of elementary connections, clusters etc., aeroelasticity of dynamically-similar models and up to testing full-scale large parts of aircraft or whole real flight vehicles.

Component testing labs are equipped with different electrohydraulic machines (1÷2,500 tonforces), which can create both static and re-static loads at a given (programmed) loading spectrum, including heating, humidity (for components and aggregates made of composite materials) and vibration effects, which simulate real operational conditions. It enables investigations of both mechanical characteristics of materials and structures, and also fatigue and crack-resistance characteristics. For full-scale structure testing TsAGI has a static test laboratory of an area of 3,600 m^2 (Fig. 27), and service life test laboratory of 6,300 m2 in area. The multichannel automatic loading systems (up to 120 channels per one test object) enable testing of flight vehicles with takeoff weight up to 250÷300 tons. The automated measuring system provides registration of up to 10,000÷18,000 pressure transducers, deformation sensors etc.

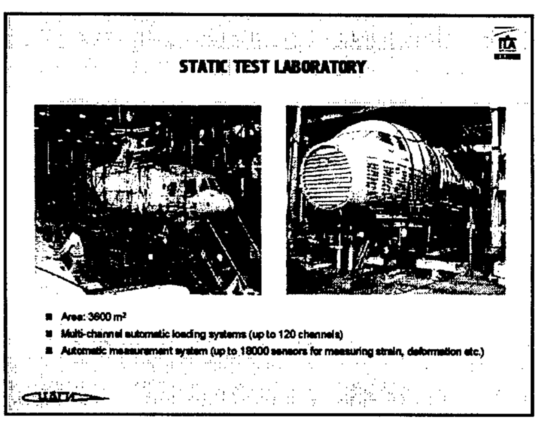


Figure 27

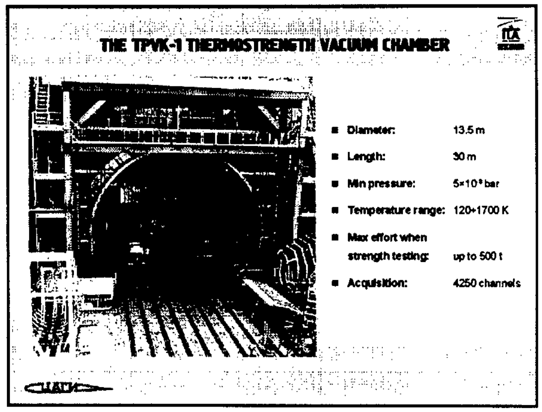


Figure 28

Complex of thermostrength chambers available at TsAGI includes 8 facilities of different size, from small ones up to a unique thermostrength vacuum chamber TPVK-1 (Fig. 28), which is intended for investigating strength of full-scale space and hypersonic vehicles. Diameter of the chamber is 13,5 m, length – 30 m. Minimum pressure (rarefaction) 5×10^{-8} bars. Maximum temperature – 1,700 K, minimum temperature – 120 K. Maximum effort at structural tests is up to 500 tons. Multichannel programmed heating (up to 92 channels) and loading is available. Number of measurement channels – up to 4,250.

Among the acoustic strength test chambers there is a unique reverberation chamber RK-1500 (fig. 29) with test section of 15,4×11,5×9,2 m and the level of the generated noise up to 164 dB. The reproduced frequency range is 45÷20,000 Hz. The accuracy of keeping to a given noise spectrum is ±3 dB per 1/3 octave. Number of measurement channels – 256.

TsAGI has gained a wide experience in designing and manufacturing dynamically- and elastically similar models of flight vehicles, including those made of modern composite materials (Fig. 30). It also possesses unique techniques for wind tunnel investigations of aeroelasticity phenomena at subsonic, transonic and supersonic speeds (Fig. 31). TsAGI's specialists have developed an advanced technique for analysing air vehicle's behavior at preflutter modes. It is used for wind tunnel and flight

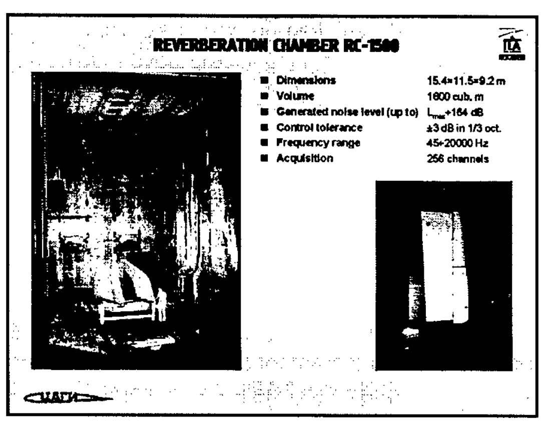


Figure 29

Figure 30

tests of real flight vehicles, including tests, when the availability of automatic control systems and active load and oscillation damping control systems is taken into account.

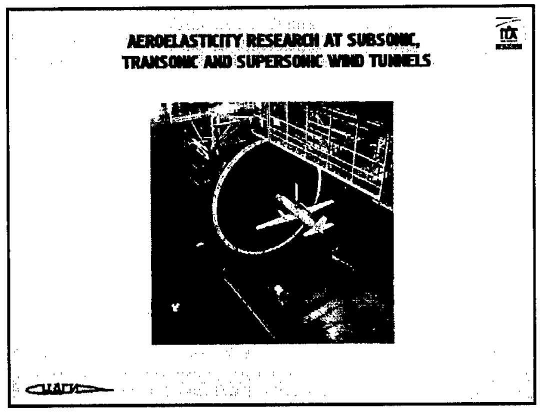


Figure 31

Paul C. LYON

Mr. Paul C. Lyon
Director New Business Development, Europe

E&S **EVANS & SUTHERLAND**

Mr. Paul C. Lyon received Bachelors and Master's of Engineering degrees in Electrical Engineering from the University of Utah. He has been employed by Evans & Sutherland Computer Corporation for 22 years. During that time, he has been an image generator design engineer, VLSI chip engineer, and a manager in the simulation display design group for twelve years. Mr. Lyon has designed integrated circuits, high-speed processing boards, various display projectors, and has done extensive system design work for all types of simulation applications. Mr. Lyon is currently the Director of new business development for Europe.

WHAT IN THE STATE OF THE ART IN VISUAL SYSTEM TECHNOLOGY FOR TRAINING ?

Bump Texture Mapping

- Provides dramatic surface relief
  - Especially useful for rough water surfaces
- Combines pixel-lighting and texture mapping technologies
- Uses texture map values to perturb per-pixel surface normals
  - No processing penalty

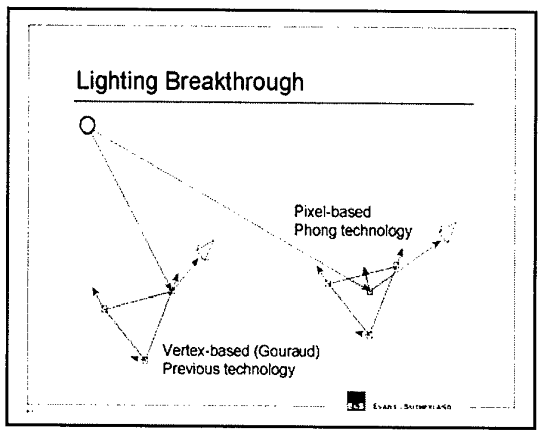
E&S EVANS & SUTHERLAND

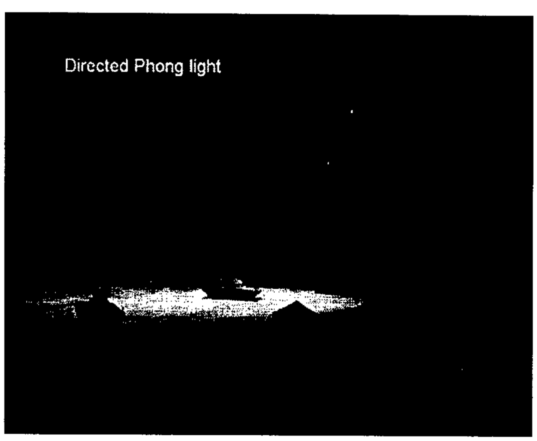
What is the State of the Art in Visual System Technology for Training?

New Visual System Capabilities

Real Time Visual System Capabilities That Didn't Exist Three Years Ago

- Phong shading
- Bump mapping
- Textured, layered fog
- Anisotropic texture (SuperTexture)
- Sensor texture
- Dynamic shadows
- Optimized Z-buffer
- Physics-based atmospherics
- Extremely large correlated databases

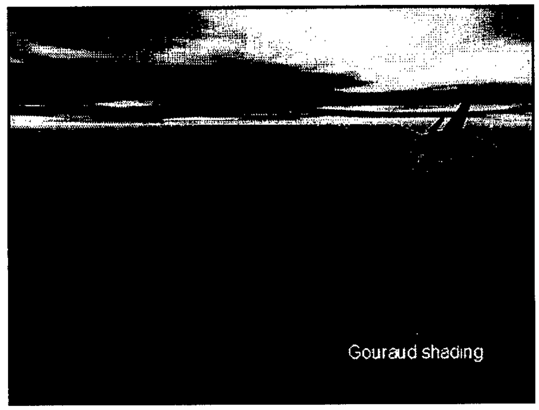




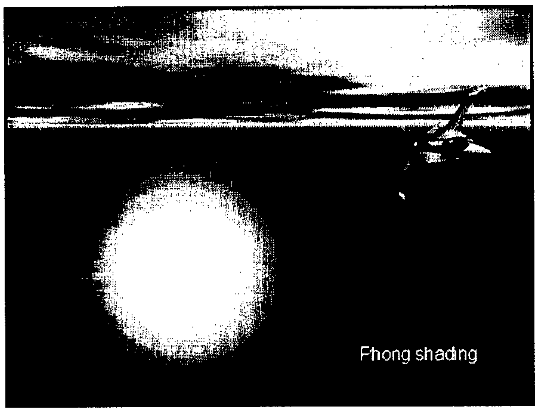
Phong Lighting

Texture

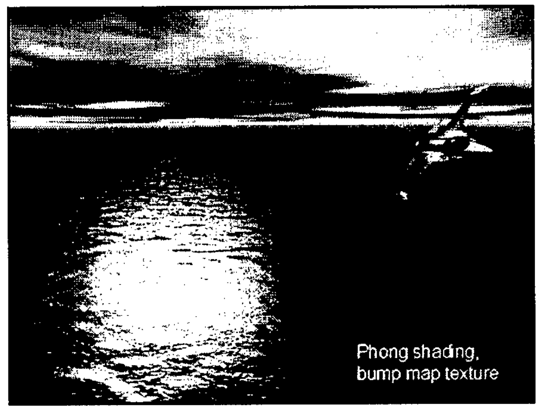
Texture with bump mapping



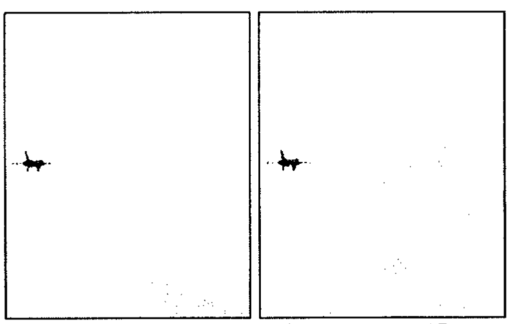
Gouraud shading



Phong shading

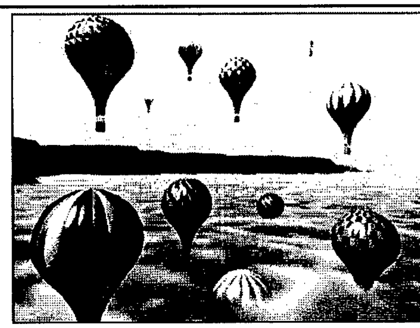


Phong shading, bump map texture



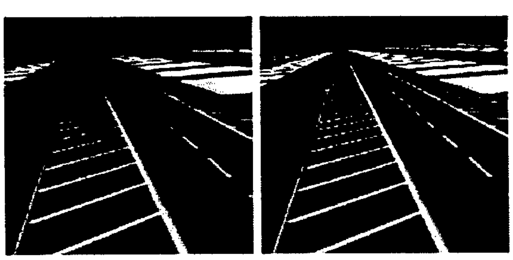
Layered Fog

Textured, Layered Fog



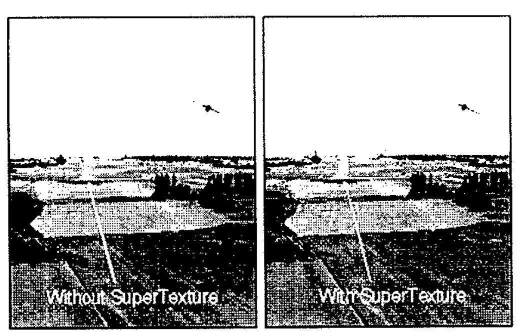
Textured Layered Fog

Anisotropic Texture (Super Texture)



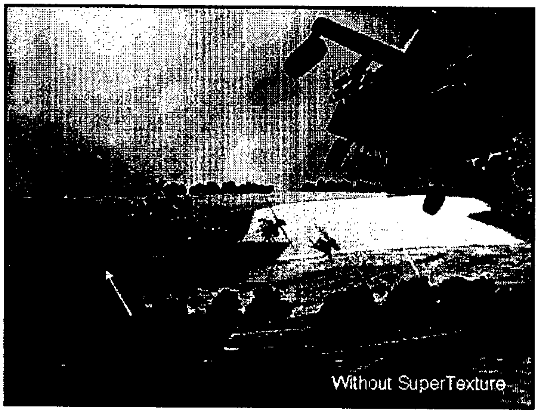
Without SuperTexture

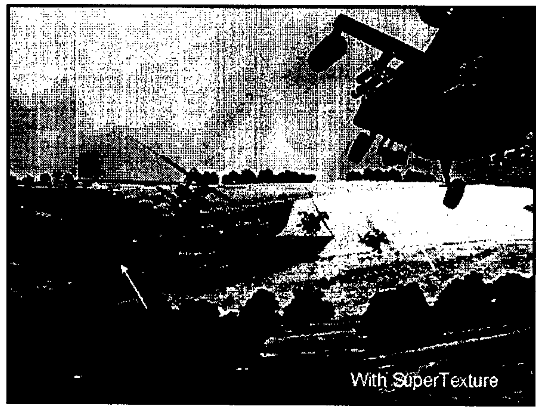
With SuperTexture



Without SuperTexture

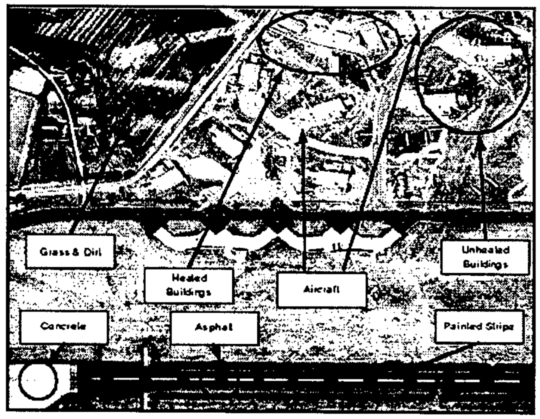
With SuperTexture

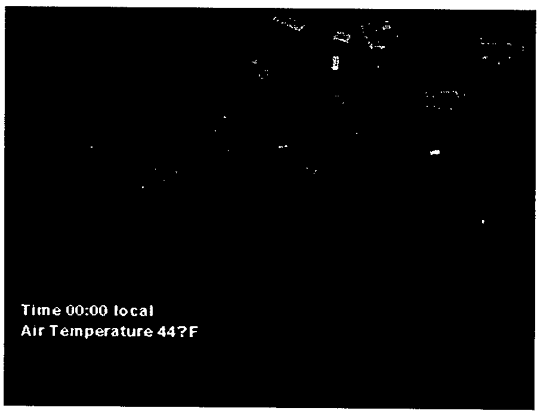


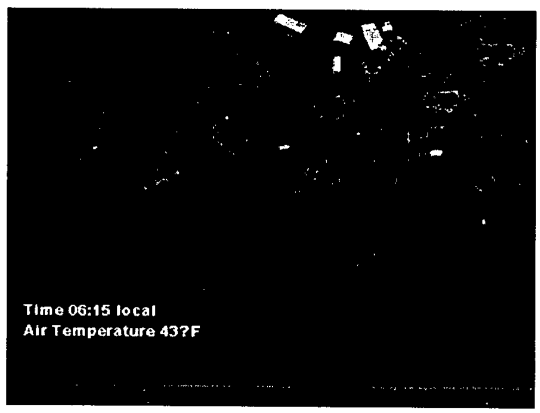


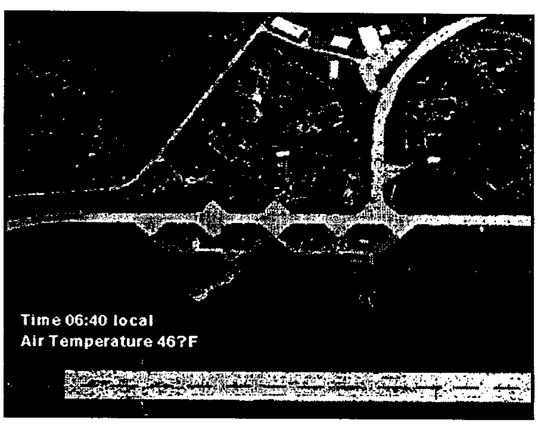
SensorTexture™

- Texture elements contain references to materials
- Physical material database contains material attributes
  - Emittance, reflectance, absorptance, density, thermal conductivity, specific heat
- Dynamic exitance calculated and rendered per texel
- Atmosphere transmission and scattering calculated by MODTRAN
  - Controllable parameters are: temperature, humidity, precipitation, pressure, and aerosol content
- Video processing applies sensor effects
  - Noise, automatic and manual gain and level, AC coupling, element failures, white-hot/black-hot switching









Dynamic Shadows

- A by-product of the E&S Sensor Texture implementation is the ability to do dynamic shadows
- Why are dynamic shadows important for training?
  - Initial requirement came from the USAF for night-vision goggle training
  - Need for realistic moon shadows that change during a mission
- Harmony-EPS

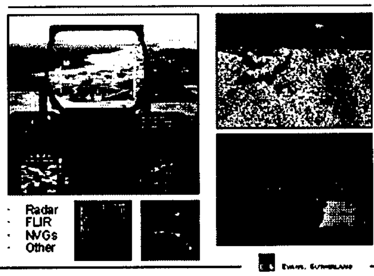
Optimized Depth Buffering

- Automatic screen-coverage optimization
  - Dramatically reduces depth complexity
- Excellent anti-aliasing
  - 16 samples per pixel yield extremely crisp edges
  - Clean inter-penetrations
- Accurate transparency
  - Continuous levels (no stepping)
  - Order-independent (no modeling constraints)

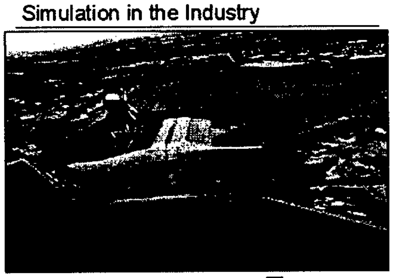
Extremely Large Databases

- New storage devices allow for larger databases to be generated
- Large, photo-specific databases that are fully correlated for out-the-window, FLIR, radar and nigh-vision
- New areas of research are beginning as companies try to solve the problem of handling the massive amounts of data required
  - Material data for every texel in a large database?

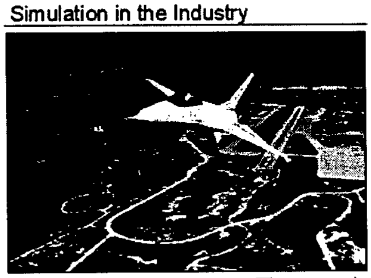
Correlated Radar/Sensor Systems



E&S Offers the Most Realistic Visual Simulation in the Industry



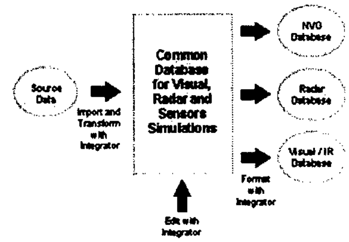
E&S Offers the Most Realistic Visual Simulation in the Industry



Physics-Based Atmospherics

- MODTRAN model - accurate for visual through infrared
- Parametric - can be set to real-life conditions
- Real time weather inputs
  - Mission rehearsal
  - Night-vision goggle training

Correlated Database Modeling using Integrator Software



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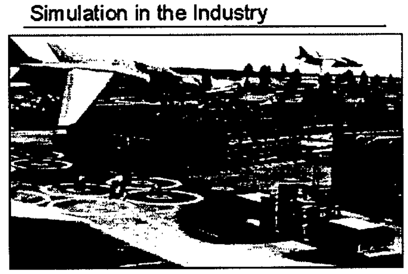


E&S Visual System Solutions

Dr.-Ing. Gerhard HEFER

Summary of professional development:
Year of birth: 1939

1966 Dipl.-Ing. of Aeronautical Engineering at Berlin Technical University
1975 Doctor's degree at Braunschweig Technical University (Prof. Schlichting)
1967 – 1987 Research Scientist at DLR Goettingen, Institute for Dynamics of Rarefied Gases and Institute for Experimental Fluid Mechanics
1977 – 1978 Member of the project team for the development of an „Intense neutron source" at Los Alamos Scientific Laboratory, New Mexico, USA
1980 Member of the Technical Group for the design of an European Transonic Wind tunnel (ETW)
1987 – 1990 Head of the Section for High Speed Flow at DLR Goettingen
1990 – 1993 Head of the Section for Dynamics of Rarefied/Real Gases at DLR Goettingen
Since 1994 Manager „Aerodynamics and Projects" at the European Transonic Wind tunnel (ETW)

THE EUROPEAN TRANSONIC WINDTUNNEL, A FACILITY FOR HIGH REYNOLDS NUMBER TESTING

Abstract

The European Transonic Windtunnel (ETW) provides the capability of achieving full scale flight Reynolds numbers by testing at high pressure (up to 4,5 bar) and at cryogenic test temperatures down to 110 K. To fully exploit the unique potentialities of the facility, a high standard of measurement quality and the understanding and avoiding of detrimental effects is necessary. The paper reviews the recent experience of testing on modern aircraft configurations over the complete test envelope of ETW. After a discussion of the test section flow quality, the data quality for short term, medium term and long term repeats is presented including tests with combined force/moment and pressure measurements at cryogenic temperatures. Examples of disturbances influencing the data quality are discussed. In addition, some results gained with the recently commissioned half model test technique are presented.

Introduction

The ETW facility is a high Reynolds number transonic wind tunnel with a partially slotted test section of 2.0 m × 2.4 m. It uses nitrogen as the test gas. With the combined effects of low temperatures and moderately high pressure, Reynolds numbers of up to 50 million at cruise conditions for full span models of large transport aircraft are achieved. The operational temperature range is 110 K to 310 K and the pressure range is 125 kPa to 450 kPa. The Mach number range is 0.15 to 1.3.

To establish with high precision aerodynamic coefficients and their small increments in this unique test environment it is necessary to guarantee an excellent quality of the measured data. This requires a superior flow stability in the test section, a very accurate surface and contour quality of the test assembly and a perfect accuracy of the tunnel and model instrumentation throughout the complete test envelope.

However, even by achieving the best flow conditions in the test section, it has to be taken into account that tunnel effects on flow conditions, effects of interferences of test section walls and test assembly supports, aeroelastic distortion of the test assembly or operation and calibration characteristics of involved instrumentation must be corrected as accurately as possible. Therefore it is essential to identify and to understand all sources of possible disturbances during testing in general. For high Reynolds number testing in the complete temperature and pressure range of a transonic facility this is even more challenging. In this particular case, for example, it must be possible to separate true Reynolds number effects from any pseudo Reynolds number effects induced by flow conditions, structural interferences, calibration methods or test assembly deformation.

With its individually controllable test parameters of velocity, temperature and pressure, ETW provides unique capabilities to especially concentrate on the achievable data accuracy. It has been proven in several campaigns, that due to the perfect repeatability of flow conditions the measured data repeatability for short, medium and long term repeats is considered excellent and demonstrates the ability to measure accurately small drag increments with very high confidence levels. The effects of wing distortion, for example, can be investigated in detail by repeating polars at constant Reynolds number at different dynamic pressures.

Additional optical installations in the test section walls also allow a direct measurements of wing distortion. The implemented cryogenic thermographic techniques provide further improvement of analysis of data during investigations of Reynolds number effects.

* Group Leader Projects at ETW GmbH
**Manager Aerodynamics and Projects at ETW GmbH

Flow Quality In ETW

During the main period of early operation and the calibration phase of ETW in 1994 to 1996 the specified flow quality and data accuracy requirements were achieved. The first test campaigns with Client models during 1995 to 1997 were also used to build up the basis for the high standard of data accuracy.

The three parameters which can be measured directly to define the tunnel conditions are static and stagnation pressure and stagnation temperature. ETW operates three flow reference systems, two of which are permanently installed and operated at the tunnel circuit. To avoid corrections for aerostatic errors both systems are mounted at tunnel centreline level and use horizontal pneumatic tubing to the total and static pressure taps. In order to assure sufficient accuracy and resolution, three pressure ranges for pt-ps are necessary.

The specified Mach number stability in the ETW test section is achieved well within its limits. Pitch/pause polars present a Mach stability better than ±0.0005 within the measured data points. During polars with a continuously pitched model the second throat is activated. Typical deviations in Mach number at high Reynolds number are presented in figure 1 for a transport configuration in a continuous pitch mode of 0.25 degrees per second. Four repeats of a polar with the same model configuration are presented and 98% of all data points are within the specified ±0.001 tolerance.

For the same test assembly the deviation of static pressure is presented in figure 2 for two polars, with and without second throat active. The 1 drag count tolerance band for these polars in static pressure is 0.001 of the full scale value, which correspond for the requested Reynolds number of 28×10^6 at Mach 0.82 and a total pressure of 360 kPa to 230 Pa accordingly. The plotted data of figure 2 demonstrate that with second throat all data are well inside the tolerance band. Without second throat 90% of the measurements are within the tolerance band.

The injection of liquid nitrogen allows a perfect temperature controllability throughout the test campaign at any level in the normal operating tem-

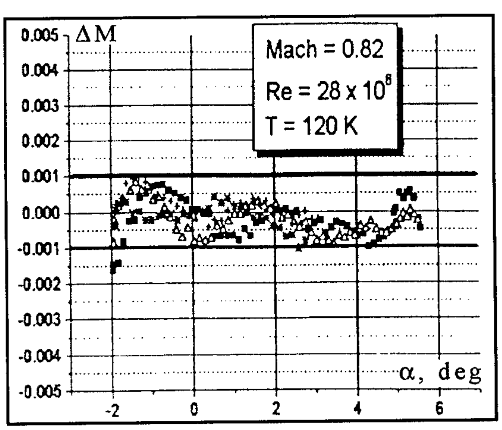


Figure 1: Mach Stability at High Reynolds Number

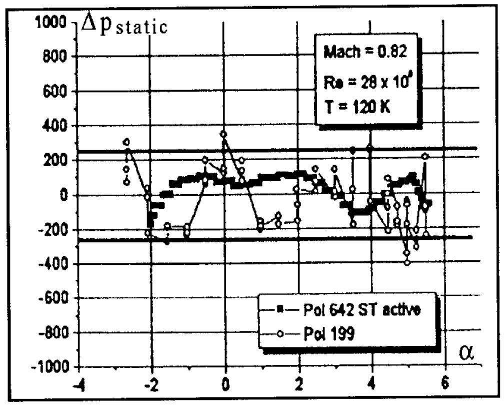


Figure 2: Stability of Static Pressure

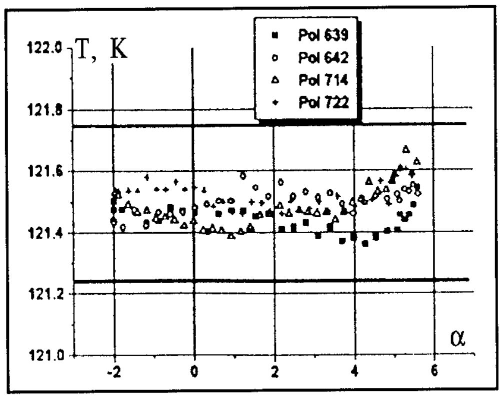


Figure 3: Temperature Stability

perature range of ETW (310 K to 110 K). The temperature can be kept constant within ±0.1 K as presented in figure 3 during 4 polars at 120 K in two different test runs.

Flow angularity and flow curvature are checked frequently throughout test campaigns, especially after significant changes of the temperature level. The standard values measured throughout all campaigns is in the range of 0.01 to 0.03 degrees. The slight increase is normally observed with decreasing temperature. Flow curvature is normally defined as a correction to pitching moment coefficients and are in the order of $\Delta C_m = 3$ to 6×10^{-4}.

Test Assembly Standards

Instrumentation

The instrumentation for measurements of tunnel conditions or model parameters has been selected, calibrated, and adjusted for temperature effects in order to meet the above described flow quality and data accuracy. The three main components of the model instrumentation are the strain gauge balance for force/moment measurements, the model inclinometer for angle of incidence measurements and the scanner units for pressure measurement.

The ETW balances are calibrated in the automatic balance calibration machine in temperature steps of 25 K between 325 K and 100 K. The achieved accuracy for the three main components of normal force, axial force and pitching moment

during the measurement is within the specified limits of 0.1% to full scale forces and moments.

The measurement of the angle of incidence is performed with a q-flex unit installed inside a thermally controlled housing. The accuracy of better than 0.01 degree is regularly achieved. The resolution of the instrument is 0.001 degree.

The overall accuracy of the model mounted high speed electronic scanning pressure measurement devices during operation is within 0.02%. The scanner units are also thermally controlled during the test campaigns and the internal temperature is stabilized to a temperature level of about 320 K.

Surface Quality

High Reynolds number testing requires a high standard of model contour accuracy and surface finish quality. The interface structure of individual model components and the internal arrangement of instrumentation and wires also have to be considered carefully and selected for the special cryogenic aspects of the test campaign. The models tested so far in the complete cryogenic test range of ETW were provided by the clients with a very high standard of surface polishing. The achieved average surface roughness values for typical ETW models were in the order of $Ra_{max} \leq 0.15$ μm. These values were even exceeded on the wing leading edges. ETW carefully inspects the model surface and performs detailed measurements of the most critical areas of the wing leading edges prior to the test campaign. Any discontinuities detected at the surface are discussed with the clients and have to be prepared for high Reynolds number test conditions by further polishing or even local repair work. A typical result of a measurement is presented in figure 4.

Additional effort is necessary if measurements with the infrared camera systems are planned. ETW provides the possibility to paint the models in cooperation with a local specialists team. The coating for all IR measurements has to be applied with great care to ensure a uniform layer of normally 0.1 mm on all the model surfaces. A very careful polishing is necessary to achieve similar surface roughness values as with the metal surfaces. In figure 4 the roughness values for the painted surface are also indicated. Normally values in the order of Ra = 0.25 μrn can be achieved.

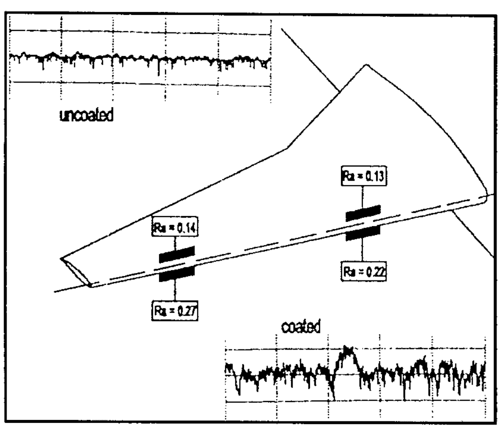


Figure 4: Wing Surface Roughness Measurements

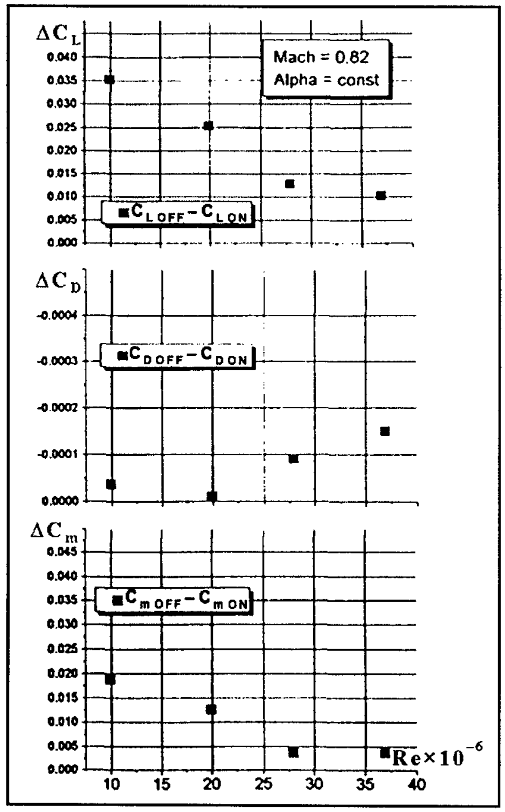


Figure 5: Influence of Coating on Aerodynamic Coefficients

The influence of model coatings was investigated in detail during several test campaigns. Typical values measured by comparing force/moment polars with and without paint are presented in figure 5. The drag values for transport aircraft configurations increase in the order of 2 to 3 drag counts at the high Reynolds numbers.

The lift coefficient C_L is affected by ΔC_L in the order of 0.01 to 0.02 and the difference in the measurement of the pitching moment coefficient C_m varies between 0.02 and 0.03. The measurements with and without painting were performed with two different models of transport aircraft models. Similar results were achieved in both test campaigns.

Test Assembly Set-up

All individual joints of the model components have to be carefully sealed to avoid any ventilation effects at the wing or fuselage components. Due to the significant forces on the components and the additional cryogenic temperature test conditions the sealing concepts need to be carefully selected. The special dentist material (Xantopren) as model sealant has so far been used very successfully.

Further care has to be taken with the model wiring. The combination of force/moment and pressure measurement significantly increases the amount of cables and wires to cross the balance. Temperature effects on the elasticity of the different materials used cannot be avoided. By careful routing of the

internal wiring it has to be ensured that no effects due to changes in temperature are influencing the quality of the data measured during the complete campaign. In the paragraph below, data will be presented for a comparison measurement with and without wires installed for pressure measurement.

Force and Moment Measurements

The short, medium and long term repeatability has been intensely studied during several test campaigns with the ETW Reference Model and with client models over the complete operating envelope of the facility.

Short Term Repeatability

During the proceeding test programmes it is standard at ETW to perform short term repeats in certain intervals to allow a continuous check of data quality. Because of the significantly different test conditions of low and high Reynolds number test runs, with changes in dynamic pressure from 20 kPa to 130 kPa within a temperature range of 110 K to 310 K, the condition of the test assembly with its instrumentation has to be carefully monitored. During a test run it is the standard practice to repeat at least one test condition for immediate check-out of data quality. In some cases special repeatability checks are performed during client tests at different tunnel conditions to establish references to data quality. Figure 6 presents the data from 6 polars at a Reynolds number of 30×10^6, a Mach number of 0.80 at a temperature of 120 K. Different pans of the C_L versus alpha, C_D versus C_L and C_m versus C_L curves are zoomed in to show the distribution of data points. The small increments of the aerodynamic coefficients (ΔC_D = 1 drag count, $\Delta C_L = 0.01$, $\Delta C_m = 0.001$) are indicated in the plotted area.

Figure 7 presents the deviations referenced to the mean value obtained from 6 polars. The figure presents an excellent short term repeatability of C_L versus alpha with $\Delta C_L < \pm0.002$, C_D versus C_L with $\Delta C_D < 0.0001$ and C_m versus C_L with $\Delta C_m < 0.001$.

The above selected polars are the direct output of the measurements with all relevant tunnel corrections included, but without any further smoothing or interpolating actions. The discussed curves are presented with a deviation from a polynomial of a selected order which is the average function of all selected polars. This relatively simple method was selected to allow an immediate discussion of the quality of results with the client during the ongoing test campaign. Further investigations, even by introducing a confidence level, can be performed in more detail after the test runs are completed. However, it has been found that a complex investigation

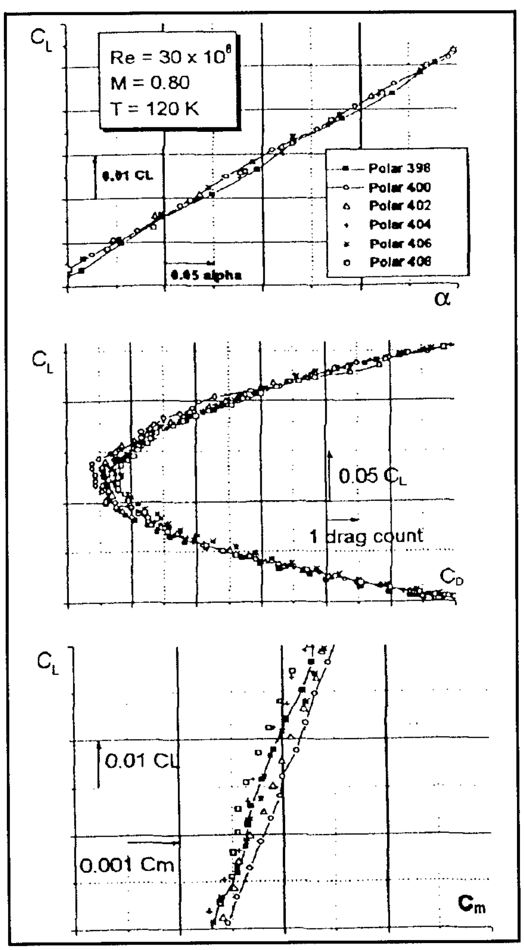


Figure 6: Selected Data Points of Repeatability Checks

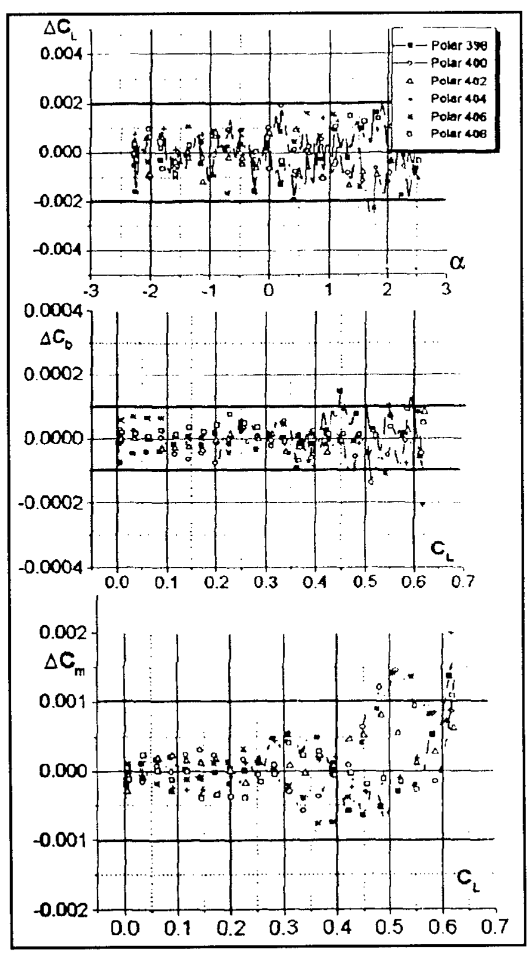


Figure 7: Deviation of Aerodynamic Coefficients

was not necessary, since all data of any repeats are of excellent quality.

Medium Term Repeatability

The medium term repeatability is defined as a repeat of the same configuration in one test campaign, with a configuration change in between and one or even more test runs of a different configuration. In this case the data are certainly very much dependent on the overall quality of the model assembly and its individual components.

For this reason, the ETW Reference Model has been designed to guarantee model build repeatability for medium and long term checks. The model consists of only three parts (nose, centre fuselage with wing and the rear fuselage) without any bolts at the outer surface of the model. Any change in instrumentation, even the exchange of balances, opening and closing the model fuselage due to instrumentation changes is absolutely without any influence on the data. This has been demonstrated several times during ETW early operating experiences.

The medium and long term repeatability of models, which consist of much more complex structures, is influenced by the model handling quality achieved during the configuration changes of a test campaign. For example, the quality aspects, together with the high envisaged productivity, required a careful selection of filler materials for cryogenic testing conditions. Therefore, at ETW, the exchange of wing components in cold environment and the unavoidable use of filler materials for the bolt head holes at the model surface has been investigated intensively during the Cryogenic Technology Programme, which was performed during the construction phase of the facility in 1988 to 1993.

A fusible alloy has been selected. It provides a combination of high thermal stability, good mechanical characteristics and the application possibilities on cold model structures. With the experience gained in several cold handling campaigns, the model configuration changing procedures have reached a high standard at ETW, which guarantee excellent medium and long term repeats in the facility at each temperature level.

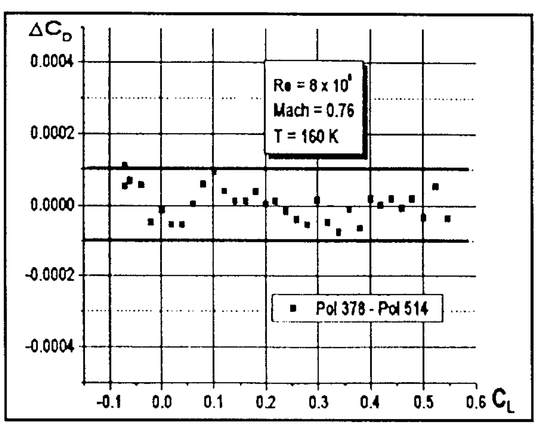


Figure 8: Deviation of Polars in Medium Term Repeatability Check

Results are presented in figure 8 showing the deviation of a medium term repeatability of C_L versus C_D curves.

The polars were taken within one test campaign, after two configuration changes and two cool-down periods, within a period of 2 weeks. The model used had a rather complex wing structure with a significant amount of filler material involved. Figure 8 demonstrates that the repeatability goal of 1 drag count was reached.

Long Term Repeatability

A client model, which is used for a second test campaign, will normally be checked for repeatability with one of the previously used configurations at the start of the new test campaign. By definition a long term repeatability check is performed if between the two tunnel entries the model assembly was completely dismounted and the facility has been used for other test campaigns.

Here again, the statements of the required high standards of model assembly quality mentioned above are valid, since additional uncertainties are involved, if the model handling activities are performed by different personnel.

The presented data of the main aerodynamic coefficients in figure 9 were obtained with a client model providing an identical configuration set-up after a period of 2 years between the first and the

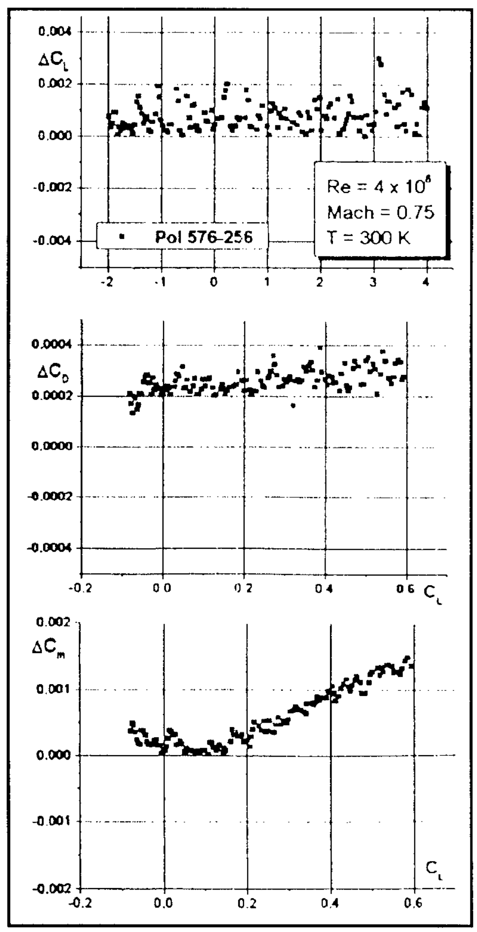


Figure 9: Long Term Repeatability

second tunnel entry. The model components of the fuselage were rather complex, but the wing was of a solid type with only few components involved. The repeat was performed at ambient temperature and low Reynolds numbers only.

For the drag coefficient an offset of about 2 drag counts was observed. The lift coefficient was within ±0.002 and the pitching moment coefficient was repeated extremely well within ±0.001 over the complete alpha range of the polar.

Balance Temperature Stability

The exact repeatability of tunnel conditions and the perfect repeat of the external model configuration have been discussed above. The next important aspect, which took a lot of effort during early investigations and feasibility studies for a cryogenic test facility, is the use of a non-heated strain gauge balance.

The general accuracy problems of these concepts were discussed in great detail from the beginning of cryogenic testing. During the first years of operation significant experience was gained with these instruments in the complete operating range of the cryogenic facility.

However, for high productivity of cryogenic facilities it is essential that the balances can be conditioned to the required temperature level of the next test run with the same speed as the model itself. This has been partly achieved with the implementation of a special balance conditioning system installed inside the model assembly, which accelerates the conditioning time of the balance. A further improvement could be made if the balances would be operational with significant temperature gradients across the balance body. Although significant effort has been applied to clarify balance accuracy and data quality under certain gradient conditions a well defined gradient correction method has not yet been identified. Therefore all balances used at ETW currently present certain limits for allowable gradients across the balance, which still results in balance conditioning periods prior to test runs.

During a normal test campaign a careful check is performed to ensure that the used balance has reached the thermal limits specified for this type

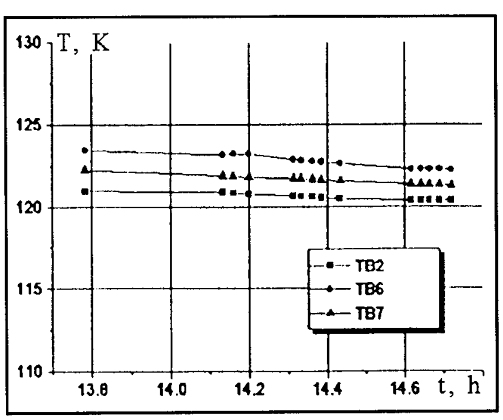


Figure 10: Temperature Stability of a Balance during a Test Run

Reynolds Number [10^4]	Mach	Total Pressure [kPa]	Total Temperature [K]	Recovery Temeprature [K]
12	0.70	418	262.4	260
12	0.75	402	262.8	260
12	0.80	389	263.1	260
12	0.82	385	263.2	260
12	0.84	380	263.4	260
12	0.86	377	263.5	260
12	0.90	370	263.8	260

Figure 11: Constant Recovery Temperature Test Programme

of balance. A typical plot of individual balance temperatures ($T_{B2} = T_{min}$, $T_{B6} = T_{Bmax}$, T_{B7}) during a long test run at cryogenic conditions is presented in figure 10. The balance temperatures in this case were kept constant within 1 K.

The thermal stability of the balance during a test run could be influenced by two parameters. First, it has to be carefully checked that no influence is seen from any internal heating devices of instrumentation housings and second, the influence of external flow conditions due to change of recovery temperature with Mach number. In both cases the model/balance joint section is affected and there is a tendency to build-up a gradient across the longitudinal axis of the balance.

In the first case the effects appear during wind-off periods in a test run. At low test temperature a heating up of the model front is recognised if no flow exists around the model for a certain time. Under these conditions the heat of the installed equipment in its heated housings (PSI housing, q-flex) is not rapidly enough transferred to the adjacent internal model surfaces. The significant heat transfer during the test run conditions at high Mach number avoids a continuous heating effect in the model nose cavity. After a break of a certain time additional temperature conditioning is required at the beginning of the next test run.

In the second case it has been noticed during the early campaigns, that the change of recovery temperature with Mach number could influence the balance stability if the test runs exceed a certain time. ETW has therefore

incorporated the possibility to perform a test run with different Mach numbers at constant recovery temperature. In that case the model and the balance are kept perfectly stable during long runs with significant changes in Mach number. A typical print of the test programme with adjusted total temperature is presented in figure 11.

Angle of Incidence Measurement

Since the q-flex incidence measurement instrument needs a stable temperature environment, a special development was necessary to produce an inclinometer housing, which is not influenced by the surrounding conditions. The

achieved design of the inclinometer box presents a perfect insulation between the ambient temperature q-flex support and the cold model structures.

However, during the design of the model it has to be taken into account that unsymmetrical temperature effects in the support structure could influence the inclinometer output. Especially, in combination with pressure measurements, where a significant heating capacity is required for the temperature stabilisation of the PSI boxes in the model nose, the design of the inclinometer box support has to be carefully selected. Inhomogeneous temperature distribution inside the model could effect the stable position of the inclinometer housing. Heat transfer from the heated joints and internal structures from the PSI heated box, and a significant heat conduction during the test runs from the wing root structure of the model has to be considered carefully. The design of the inclinometer box support has to be adjusted accordingly to minimise these effects.

The overall experience gained with the standard ETW inclinometer boxes confirms that the specified accuracy of 0.01 degree during measurements can be readily achieved together with a resolution of 0.001 degree.

Pressure Measurement

All the data presented so far included only force/moment repeatability data. The influence of pressure measurements especially for the correction of model base pressure is of significant importance. The following results in figure 12 present the short term repeats of a model at a Reynolds number of 40×10^6 and a Mach number of 0.82. The data are taken within a pitch/pause programme and are presented prior to averaging of the data for each pressure measurement at a constant alpha. The averaged data are within a deviation of 1 drag count.

The specified accuracy of the differential base pressure transducers normally used for a test assembly is 0.02%. The accuracy of the absolute transducer for the back pressure measurement is in the order of ±100 Pa. However, it has been verified in all campaigns that in practice the achievable accuracy during the test is better than ±70 Pa in the complete pressure and temperature range of the facility.

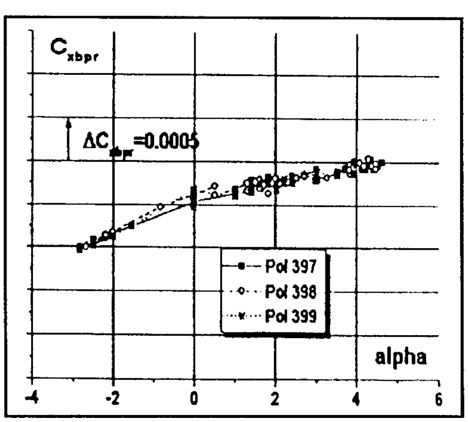


Figure 12: Repeatability of Base Pressure Measurement

Combined Force/Moment and Pressure Measurement

A further aspect in repeatability of data is the influence of internal model arrangements with instrumentation wiring crossing the balance from the metric to the non-metric part. For a pure force/moment measurement the wires used are very thin and with standard guiding of the wires there is no concern for any influence to the force/moment measurement.

It becomes more complex as soon as force/moment measurement are combined with pressure measurements. A significant amount of additional wires are used when the Electronic Scanned pressure (ESP) units are installed. The additional wires have to be treated very carefully, since in cryogenic conditions all wires change significantly their elasticity characteristics. With an excessive amount of wires the force/moment measurements could be influenced significantly. Therefore a lot of effort has been spent investigating this aspect Test runs with and without installed wires for the pressure measurement were performed to identify any possible effects from the wires. Further improvement on minimizing the required amount of wires was discussed with the manufacturer. The standard PSI cabling was then modified to reduce any parasitic interference on the measurement. However, the total amount of wires and tubes is still significant as presented in figure 13.

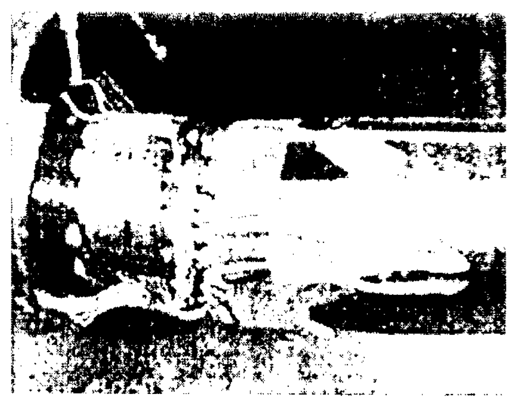


Figure 13: Installation of Wires at the Balance/Sting Joint

The repeatability of several configurations was checked for identifying any influences of wires during the most critical test conditions at high Reynolds number. Detailed checks were performed prior to tunnel testing at both ambient and cryogenic conditions to investigate possible hysteresis effects. Figure 14 presents the result of testing the configuration back to back with and without the wires installed for the pressure measurement. It is obvious from the results achieved that the differences in CD are smaller than 1 drag count.

Since the scanner units for the pressure measurement are installed inside the model fuselage and have to be operated at ambient temperatures it is always necessary to mount the units into a thermally controlled housing. Special attention has to be paid for thermal stability of the housing over the extreme

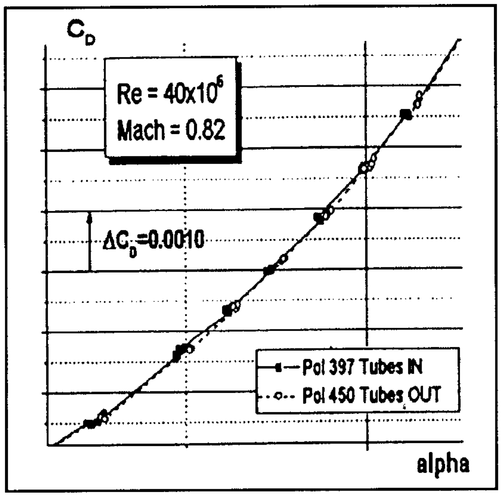


Figure 14: Measurement With and Without Pressure Equipment

operating conditions of both the upper and the lower temperature limits. The internal housing condition is normally kept constant at a level of 320 K during the complete campaign. If the housing temperature has to be changed a recalibration of the system is necessary. This could happen if significant parts of the test programme are at ambient conditions, hi that case the heat transfer to the external conditions is restricted and a higher temperature level is reached inside the box. At all test temperatures below 280 K the box temperature is kept constant.

Normally, for the complete pressure range of the facility, ESP units of 30 psi range provide an accuracy of better than ±50 Pa. With the accuracy of the absolute transducer mentioned above for the back pressure measurement the overall accuracy is in the order of ±150 Pa.

Disturbances

Model Dynamics

The data quality of measurements at high dynamic pressure can be influenced significantly by an increased level of model dynamics. Although this phenomenon is known from conventional wind tunnels as well, cryogenic tunnels seem to be particularly prone to model dynamics. Therefore, some aspects of model vibrations are discussed in the following paragraphs.

The model/balance/sting/sector/model cart assembly is a vibratory system which may be excited either by structural vibrations or by aèrodynamic disturbances. The latter may have different causes. For the sake of simplicity and in order to cover the most significant phenomena in ETW, only two characteristic effects are considered: firstly a low power broad band excitation and secondly an excitation of a special frequency given by the aerodynamic phenomenon.

Broad Band Excitation

As the internal balance is a comparatively soft spring, the fundamental frequencies of the model/balance system are rather low ($f < 70$ Hz). In the presence of a broad band excitation, the model may oscillate as a rigid body picking up eigenfrequencies given by the model mass and mass distribution and the balance stiffness for the corresponding degrees of freedom. These vibrations are detrimental for data quality, especially for the measurement of angle of incidence. Amplification may occur if there is another vibratory element with an eigenfrequency nearby (e.g. model pitch and sting bending). This may lead to strong oscillations giving rise to an interruption of the polar or even the test These vibrations have successfully been attenuated by using different balance/sting combinations, by passive damping inside the model, and by active damping. An interface based on an active damping concept is being developed by ETW and will be used with the regular ETW flange balances. The error in angle of incidence measurements is corrected by an ETW developed method based on acceleration measurements.

Buffet Onset and Wing Tip Buzz

Buffet onset is characterised by a separation induced shock oscillation, the frequency of which is given by the configuration and the aerodynamic conditions'. Figure 15 shows, qualitatively, the dependence of the reduced frequency of the shock oscillation

$$f_{red\,c} = 2\pi f_c \, c/v$$

and the corresponding amplitude $\Delta x/c$ on angle of incidence (with c = wing chord and v = velocity). With increasing separation (a genesral term for no more fulfilling the Kutta condition at the trailing edge) the frequency reduces and the shock oscillation amplitude, i.e. the exciting force, increases. The strongest excitation occurs in the region of alternating attached and separated flow causing strong changes of circulation at low frequencies. At fully separated flow, a more stable situation with high frequencies prevails.

The point of buffet onset is a matter of definition (trailing edge pressure, lift break, root bending moment, accelerations at different parts of the airplane etc.). For comparisons between wind tunnel and flight data, an aerodynamic criterion should be cho-

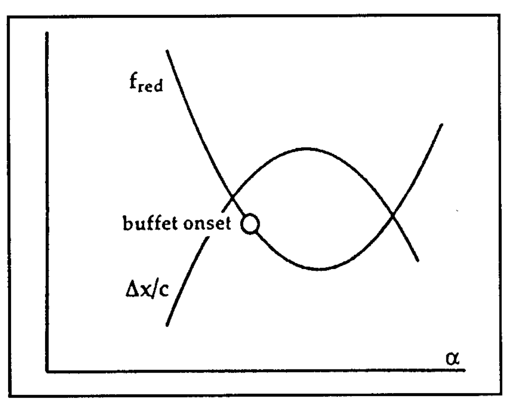


Figure 15: Buffet Onset Conditions

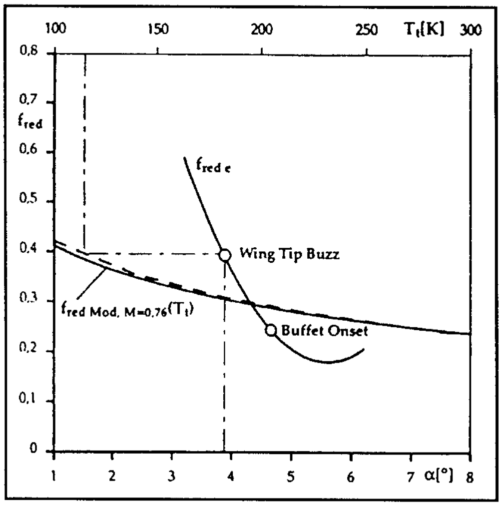


Figure 16: Reduced Frequency Behaviour

sen because the elastic and damping characteristics of model and airplane are very different.

A special mode of vibration may occur if the excitation and a vibration mode of the model (e.g. wing bending) are in resonance. This is the case if the reduced frequencies of the shock oscillation and the wing bending are equal. The reduced frequency of the wing bending

$$f_{\text{red Mod}} = 2\pi f_{\text{Mod}}\, c/v$$

is depending on temperature via v. As an example, for a model fundamental frequency of 80 Hz, a chord length of 120 mm and a Mach number of 0,76 it is plotted versus temperature (upper scale) in figure 16. The figure shows that the reduced frequency increases with decreasing temperature. The dotted line indicates the small effect of changing wing stiffness with temperature.

In addition, the general course of the frequency of the aerodynamic excitation, fred c, has been plotted. From the drawn in example (T_t = 115 K) it can be seen that at low temperatures the wing bending may be in resonance with the excitation at lower angles of incidence than buffet onset. At high temperatures, buffet may occur at a lower a than the resonance. This behaviour is in line with experimental findings.

From these results, it seems to be very likely that wing tip buzz is a resonance of wing bending and a pre-buffet high frequency excitation. An experimental verification could be done by changing the eigenfrequency of the wing, e.g. by a model design that allows varying the mass in the wing tip region.

Model Surface Imperfections

Two cases were experienced in ETW where surface imperfections on the wing created some disturbances to the aerodynamic data quality.

During configuration changes on a cold model special care has to be taken to avoid moisture entering the surrounding dry air environment of the model. Moisturized air could create immediately layers of frost on the cold model surfaces or any other cold components. A layer of frost on the balance for example will influence the output during the measurement. The detection of any frost layers on internal parts of the assembly would be extremely difficult. The concept of a cold handling model box has been specially adopted to avoid moisture problems on the model structure during cold handling activities at ETW2.

A layer of frost on the wing surface of the model was detected in ETW after a test run was performed at 120 K and it was obvious that the repeatability check at the end of the test run did not fit with the results obtained before. It was found that after cold handling activities in the dry air handling areas of the facility the model caught frost and even long purging procedures did not remove it. Detailed inspection of the model surface with a high resolution camera system confirmed the existence of a very thin layer of frost The influence to the aerodynamic data is presented in figure 17. It is obvious that a constant shift of the pitching moment coefficient appears and the lift coefficients are reduced.

A similar experience was made on a painted wing when disturbances appeared on the wing leading edge due to impacts. The ETW tunnel circuit is especially protected by extremely careful access and working procedures to avoid any pollution with particles from people visiting or working inside the tunnel circuit. The appearance of impacts on a painted wing is therefore an indication of an unusual contamination of the tunnel, the cause of which needs to be investigated. The high data quality achieved in ETW and the procedure of performing standard repeats during a run immediately highlight such occuring problems.

The effect on die aerodynamic data is indicated in figure 18. In this case it is obvious that data arc affected only at high incidence. In the buffet onset

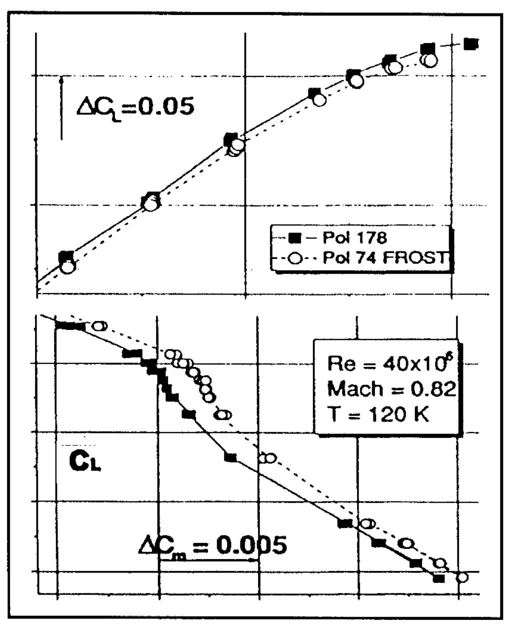


Figure 17: Influence of a Thin Layer of Frost on Aerodynamic Data

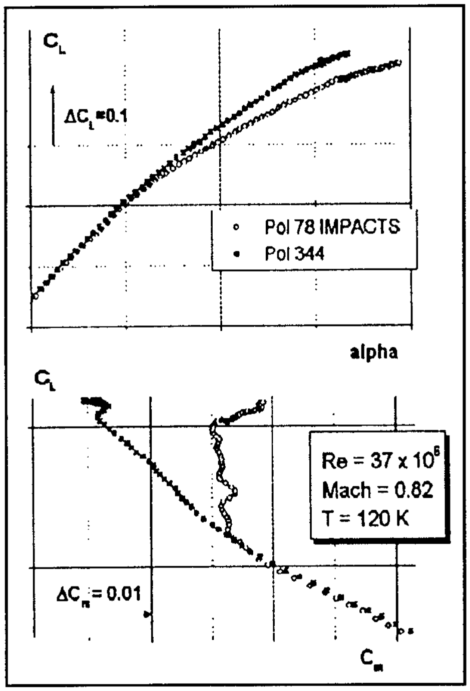


Figure 18: Influence of Model Surface Impacts on Aerodynamic Data

region both, the lift coefficient and the pitching moment coefficient are influenced significantly.

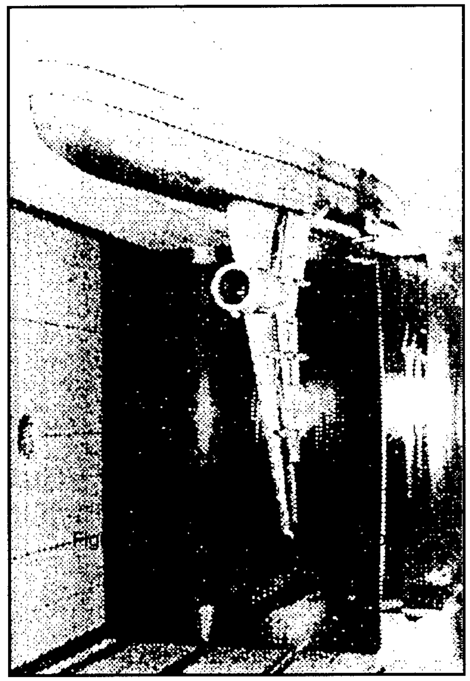
Half Model

The above presented data all refer to ETW experience with full model test assemblies which were tested since 1994. In June 1999 ETW started with the First half model commissioning and calibration activities in the tunnel. First experience was gained with the new technique in the following months, by using two different models in the commissioning, calibration and validation phase of the half model concept.

The half model cart system comprises a new test section top wall which can be exchanged with the standard top wall of model cart 1. The half model balance is installed on that top wall and the model will be mounted in the preparation areas at this top wall position. The half model systems uses a thermally conditioned balance. The thermal control system ensures that the balance is decoupled from ETW's variable temperature operating environment and has been designed to have minimal effect on the temperature of model components supported from the balance adaptor.

The balance has been designed for a combined loading in normal force of 55 kN, pitching moment of 4.4 kNm and an axial force of 5.5 kN. Accuracy is specified as a complex function of the combined operating loads. For normal force, axial force and pitching moment the accuracy is 0.1% of the maximum load over 50 to 100% of the range and 0.05% below 50%.

Figure 19 shows the overall installation inside the ETW test section.



The first results achieved with the new half model concept were very promising for the complete test envelope of ETW. The short term repeatability presented excellent data. At a Reynolds number of 26×10^6, a Mach number of 0.6 and a temperature of

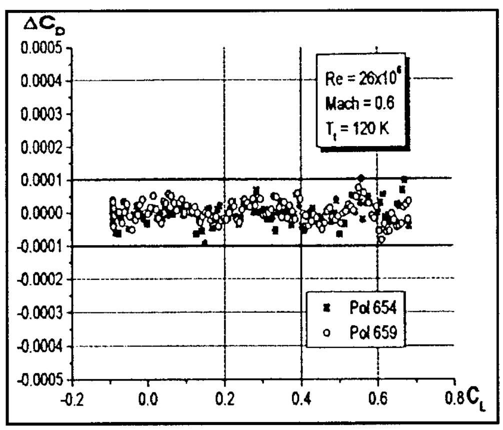


Figure 20: Short Term Repeatability of the Half Model Test Results

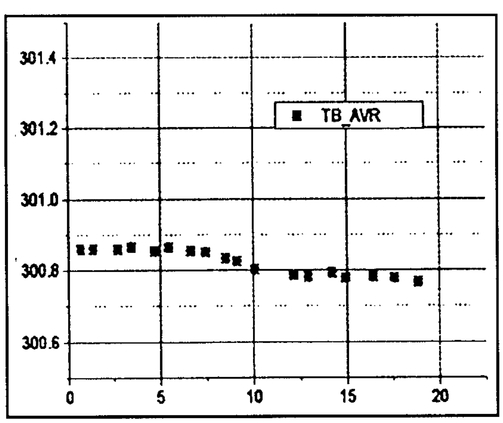


Figure 21: Half Model Balance Temperature Stability

120 K the standard deviation of the drag coefficient was well within 1 drag count as presented in fig. 20.

The data were taken during the validation testing of the concept with a typical transport configuration. As important result from the commissioning and validation testing it was noticed that the balance body temperature could be kept stable throughout all temperature, pressure and Mach number changes in the facility. Figure 21 presents the achieved balance temperature stability within a long test run at cryogenic temperature conditions.

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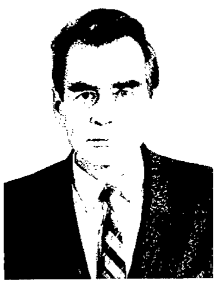


Vasily P. RUKAVETS

Deputy Director of TsAGI responsible for test facilities (since 1998), Honoured Designer of Russia (awarded by the Decree of the President of Russia in1993), author of 15 inventions (patented) and 20 published scientific articles.

Education:

1960 – graduated from the Kharkov Aviation Institute, aircraft engineering;

1972 – finished post-graduate course at TsAGI, fluid and gas dynamics.

Professional background:

Since 1964 working at TsAGI as Design Engineer, Head of Section, Head of Department, Deputy Head of Division, Head of the Wind Tunnel Test Facilities Design Division.

SOME WAYS OF SIMULATING ACTUAL FLIGHT PARAMETERS IN GROUND TEST FACILITIES

V.I. Alferov, A.P. Kurshin, V.P. Roukavets, A.V. Shustov

Introduction

A distinctive feature of TsAGI as contrasted to similar research centers in the USA, Canada, Europe etc. is that TsAGI has special divisions, which carry out permanent investigations, experimental and design activities on perfecting the already existing test facilities and creating new ones. The experience of TsAGI in this direction proves that the best outcomes can be obtained when the Customer of a test facility has close contacts and co-operation with the designers and operating staff.

Technical experts of the AGARD International Workshop on Wind Tunnels, which was held in Moscow in October, 1996, emphasised this distinctive feature of TsAGI as a very positive factor.

TsAGI gives special attention to investigating new, non-conventional schemes of aerodynamic test facilities, which ensure simulation of flight parameters' values close to real for different classes of flight vehicles. These are aerodynamic facilities with magnetohydrodynamic flow acceleration and installations with pressure multiplicator.

Aerodynamic facility with magnetohydrodynamic flow acceleration

The main distinctive feature of this installation from those of the classic scheme (where they use the principle of converting full enthalpy of slowdown to the flow kinetic energy at gas expansion in the supersonic nozzle) is the direct increase in the flow energy due to the work done by Lorentz force in the magnetohydrodynamic device. The principal layout of the installation is given in Fig. 1, and its general view and the view of the MGD-ACCELERATOR are represented in Figs. 2, 3.

On this model installation the following items have been investigated and tried out:

- air heater;
- method of flow ionisation;
- power supply modes of the MGD-ACCELERATOR ejectors;
- the MGD-ACCELERATOR design regarding structural material selection;

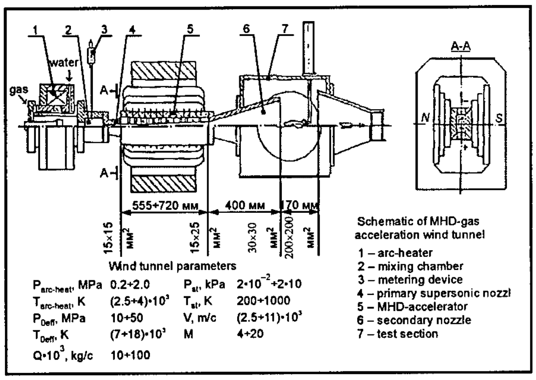


Figure 1

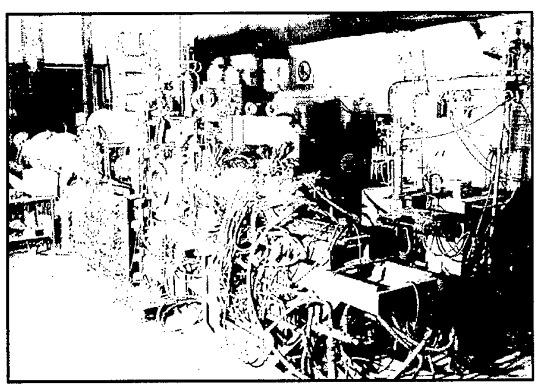


Figure 2

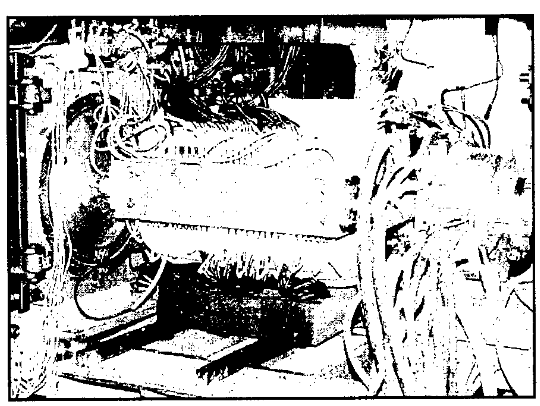


Figure 3

- technique of determining parameters of flow in the test section.

An example of visualisation of flow over the model (full pressure transducer) is given in Fig. 4.

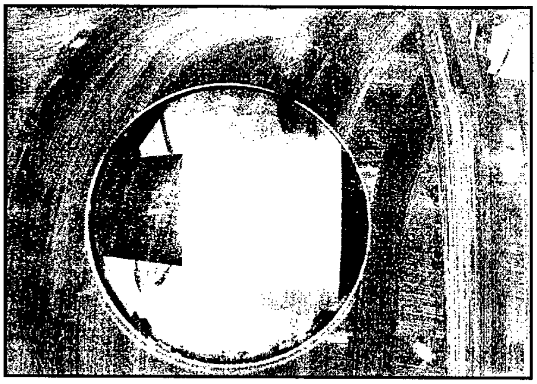


Figure 4

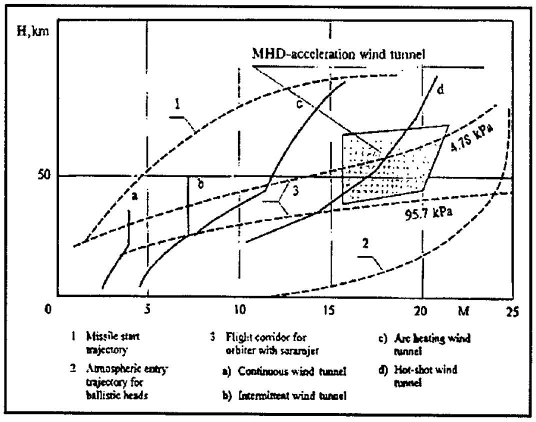
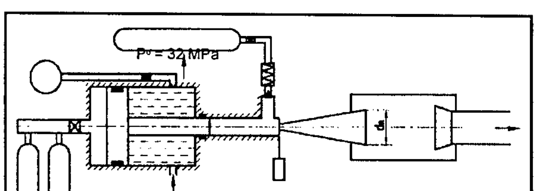


Figure 5

In Fig. 5 the probable area in co-ordinates (M, H) of the realised flight parameters is shown.

Aerodynamic facility with pressure multiplicator

The gas flow in this installation is produced at motion of the cylinder piston, which pops dense heated gas from the small barrel of multiplicator into the nozzle. The steady flow in this facility is not contaminated by mechanical impurities and operational mode is some times longer than in impulse, shock or adiabatic compression wind tunnels. The installations of the new type are very economic and have extremely low operation costs.



Parameter	Designed	Realized
P°, MPa	1000	at 500
T°, K	2200	at 2000
d	0,15÷0,30	0,15; 0,30
t, s	0,04÷0,20	0,04÷0,20
M	5÷20	5÷18
Acting gas	Air	Air

Figure 6

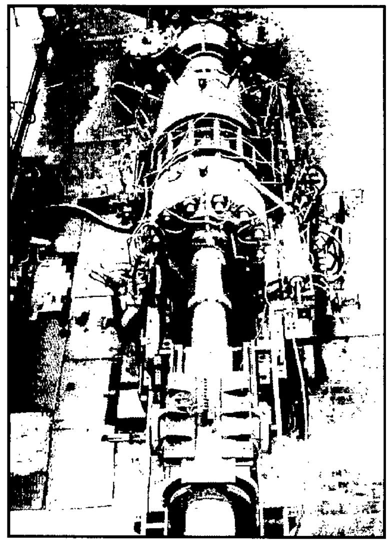


Figure 7

The principal diagram of the installation is given in Fig. 6, and its general view – in Fig. 7.

During experiments the following items have been investigated and tried-out:

- multiplicator design;
- design of the nozzle critical bay;
- design of the launching device;
- methods of models testing.

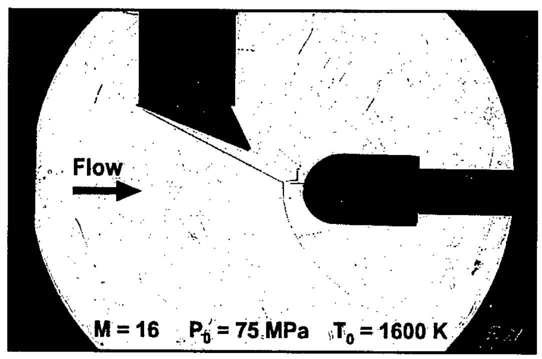


Figure 8

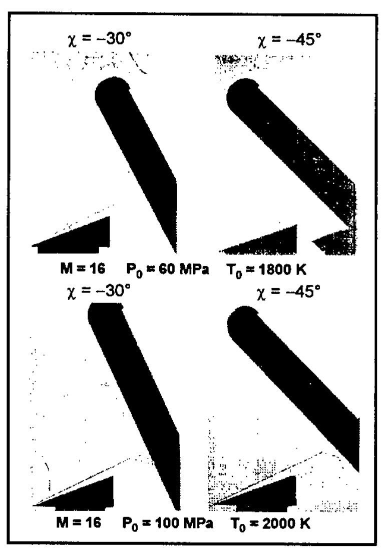


Figure 9

In Figs. 8, 9 one can see the examples of visualising shock waves – boundary layer interference on the compound models.

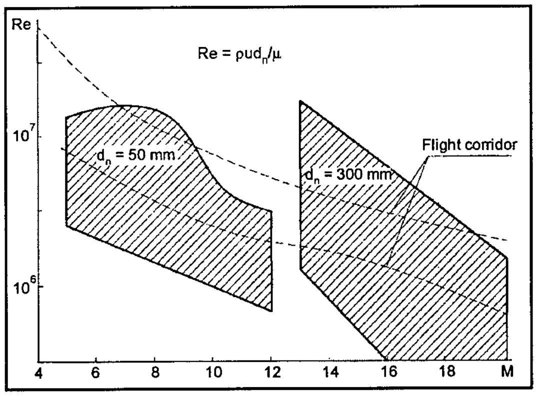


Figure 10

In Fig. 10 the co-ordinates (M, Re) area of the realised flow parameters is shown.

Development and Creation of High-Altitude Wind Tunnel for Propeller Testing

Investigations into high-altitude long endurance vehicles cover a wide range of problems associated with the configuration of these vehicles. One problem arising in developing such vehicles is the need to test large diameter propellers capable of ensuring flight at high-altitude conditions – up to 20÷25 km.

For solving this problem it is necessary to develop and create a high altitude wind tunnel. Such a wind tunnel can be created on the basis of the unique Vacuum Chamber (VC) available at TsAGI (Fig. 11). The chamber enables simulation of atmosphere conditions for altitudes from 0 km to altitudes higher than 30 km. Its dimensions are: diameter – 13.5 m, length – 30 m.

The high-altitude wind tunnel can be mounted inside this VC. Wide possibilities for varying gas parameters would allow studies on the influence of Reynolds number, temperature and other medium parameters on the characteristics of propeller and/or power plants.

The wind tunnel can be made as a cylinder with a fan driver and a tested propeller set placed inside of it. The wind-tunnel casing could be sectional, and its assembly could be made just prior to propeller testing. The wind-tunnel structure would consist of three main sections:

- section 1 – comprising the fan driver;
- section 2 – forming the working section;
- section 3 – comprising the diffuser inlet with the blades turning the flow.

Each section will be provided with appropriate equipment mounted inside of it. Connection of sections will be accomplished inside the VC by means of technological joints. The insertion of the sections into the VC will be made by means of built-in wheels.

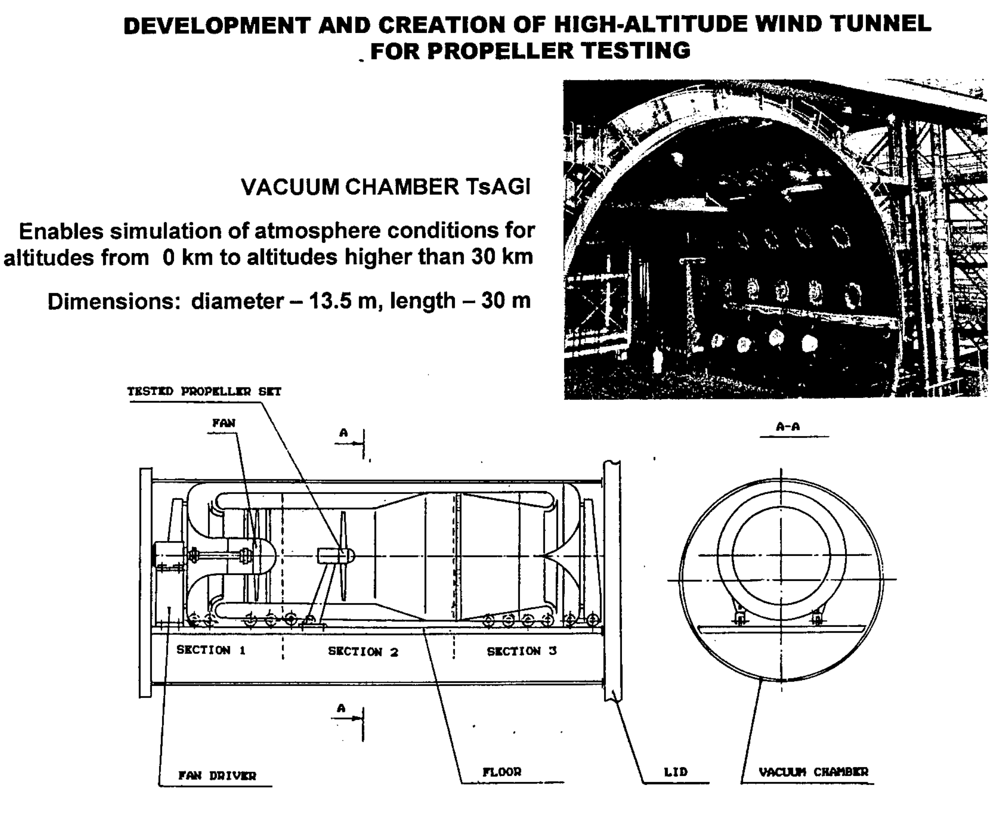


Figure 11

Because of low working temperatures inside the VC the envelope of the wind tunnel can be manufactured from aluminium alloy.

The reverse channel will be formed between the outer surface of the sections and the inner surface of the VC.

In case of placing the fan driver inside the VC its appropriate cooling will be produced by means of a special housing with atmosphere pressure air supply.

Expected Results of Development

The high-altitude wind tunnel for propeller testing with the following characteristics will be the main result of development:

- Air pressure in the working section P = 7.56÷0.58 kPa;
- Air temperature in the settle chamber T = 217÷224÷300 K;
- Flow velocity in the working section V = 5÷50 m/s;
- Maximum head pressure of the single stage fan p = 319 Pa;
- Maximum diameter of the propeller tested – 6000 mm;
- Maximum power of the power plant tested – 50 kW (up to 150 kW in future);
- Maximum flow velocity in the reverse channel:
  - 30 m/s (at inlet),
  - 33 m/s (at outlet).
- Maximum power of the fan driver – 600 kW;
- Diameter of the working section – 6300 mm.

Thus the basic potentialities of the proposed high-altitude wind tunnel consist in ensuring experimental investigations of high-altitude vehicle propeller characteristics (as well as the propeller with its power plant) in a wide range of air flow parameters.

CONCLUSION

The model aerodynamic facilities with the ÌGD-accelerator of flow and pressure multiplicator, created and investigated at TsAGI, demonstrate that it is possible to create full-scale installations for investigating flight vehicles' models at values of simulation parameters (M, Re, V, structure of gas etc.) close to real.

TsAGI has now gained practical experience in developing, creating and operating such types of installations.

Dr. Dieter HOLZDEPPE

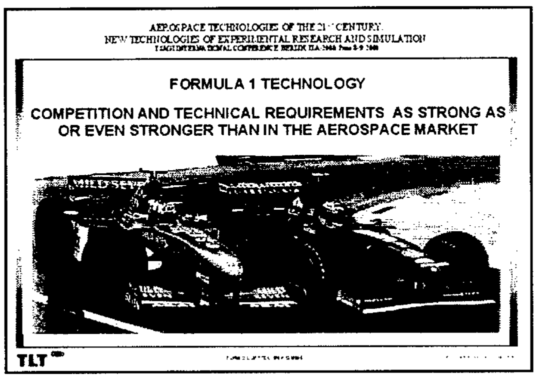
Titie: Vice President

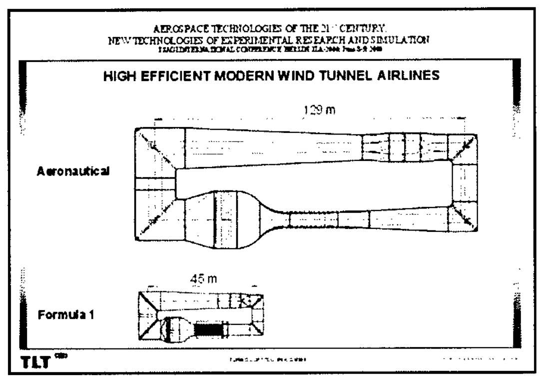
Professsonai Associations: AIAA DGLR

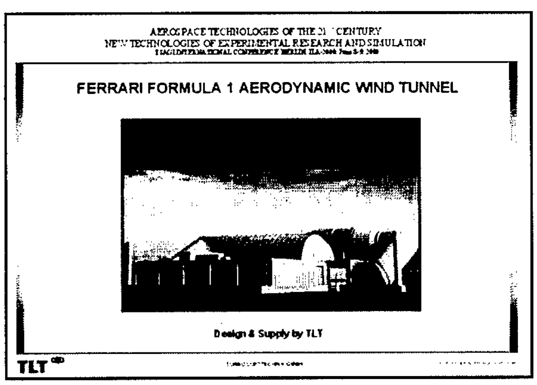
Education: Technical University Aachen (RWTH Aachen) Ph. D Aerospace Engineering, 1986

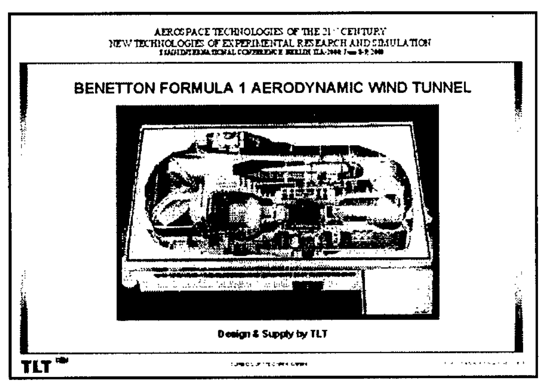
Experience: Since 1987 with Turbo Lufttechnik GmbH.
Beside other activities having been responsible for the acquisition, the design and the development of wind tunnels induding the low speed wind tunnels of the Formula 1 teams of FERRARI and BENETTON

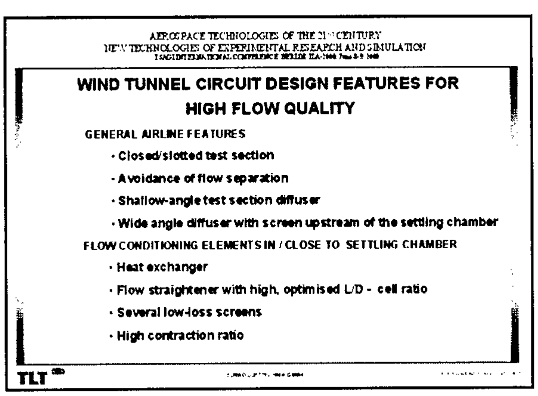
ON THE TESTING AND FLOW QUALITY IN ADVANCED FORMULA-1 WIND TUNNELS AND THE COMPARISON TO AEROSPACE FACILITIES

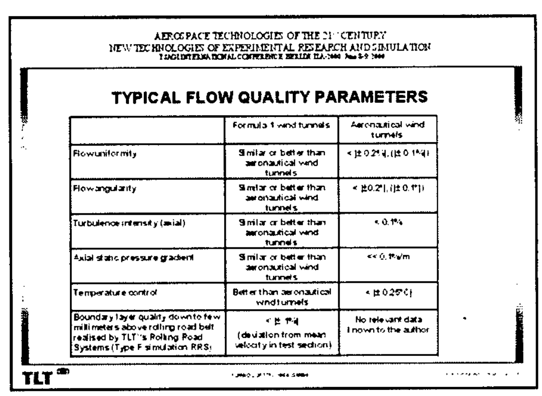












AEROSPACE TECHNOLOGIES OF THE 21st CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

TYPICAL FLOW QUALITY PARAMETERS

	Formula 1 wind tunnels	Aeronautical wind tunnels
Flowuniformity	Similar or better than aeronautical wind tunnels	< |± 0.2%|, (|± 0.1%|)
Flowangularity	Similar or better than aeronautical wind tunnels	< |±0.2°|, (|± 0.1°|)
Turbulence intensity (axial)	Similar or better than aeronautical wind tunnels	< 0.1%
Axial static pressure gradient	Similar or better than aeronautical wind tunnels	<< 0.1%/m
Temperature control	Better than aeronautical wind tunnels	< |± 0.25°C|
Boundary layer quality down to few millimeters above rolling road belt realised by TLT's Rolling Road Systems (Type F simulation RRS)	< |± 1%| (deviation from mean velocity in test section)	No relevant data known to the author

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AEROSPACE TECHNOLOGIES OF THE 21ST CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

FORMULA 1 WIND TUNNELS

MAIN FEATURES OF AERODYNAMIC F1 MODEL TESTING AND WIND TUNNEL OPERATION

- Management of separated flow fields and interference aerodynamics
- All year extensive aerodynamic optimisation of all vehicle components including adaption for the specifics of the different racing tracks
- Extreme productivity by highly automated wind tunnel control and measuring systems
- 2 shifts during complete year (minimum)

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AEROSPACE TECHNOLOGIES OF THE 21ST CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

FLOW FIELD AROUND AN OPEN-WHEEL FORMULA 1 RACE CAR

Ref. J. Katz, „RACE CAR AERODYNAMICS", 1995, Publisher Robert Bentley, Inc

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AEROSPACE TECHNOLOGIES OF THE 21ST CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

FLOW FIELD DIAGNOSTIC TECHNIQUES

TUFTING "YESTERDAY"

Ref. Volkswagen AG

TLT

AEROSPACE TECHNOLOGIES OF THE 21ST CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

FLOW FIELD DIAGNOSTIC TECHNIQUES

TUFTING "TODAY"

Ref. J. Katz, „RACE CAR AERODYNAMICS", 1995, Publisher Robert Bentley, Inc

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AEROSPACE TECHNOLOGIES OF THE 21ST CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

SOME FLOW FIELD DIAGNOSTIC TECHNIQUES

FORMULA 1 WIND TUNNELS

- Smoke
- Tufting

} standard

- Laser Sheet
- LDA
- PIV
- Oil coating
- Probe Traversing

} only occasionally used, low productivity

- CFD — standard, parallel to measurements

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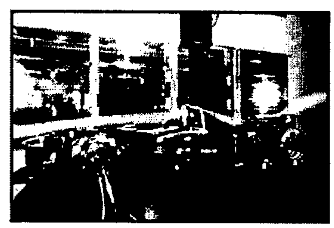
AEROSPACE TECHNOLOGIES OF THE 21ST CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

50% F1-MODEL IN TEST SECTION OF FERRARI F1 WIND TUNNEL



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AEROSPACE TECHNOLOGIES OF THE 21ST CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

WALL/FLOOR BOUNDARY LAYER CONTROL OF TEST SECTION

AERONAUTICAL WIND TUNNELS

TYPICAL REQUIREMENTS	SOME TECHNIQUES
Management of "side wall" flows in airfoil tests to simulate 2D-flowfields	Suction
Simulation of true ground effects in ground proximity testing of aircrafts	Moving Ground
Avoidance of flow breakdown in high lift testing	Blowing

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AEROSPACE TECHNOLOGIES OF THE 21ST CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

FLOOR BOUNDARY LAYER CONTROL OF TEST SECTION

FORMULA 1 WIND TUNNELS

TYPICAL REQUIREMENTS	TYPICAL TECHNIQUES
Simulation of true ground effects with extreme low-clearance Formula 1 cars	Suction together with moving ground („Rolling Road System")

TLT

AEROSPACE TECHNOLOGIES OF THE 21st CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

FLOOR BOUNDARY LAYER CONTROL OF TEST SECTION FOR THE SIMULATION OF RACE TRACK CONDITIONS

FORMULA 1 WIND TUNNELS

Best solution

- Rolling Road System with primary and secondary suction system

Other solutions

- Elevated ground plane
- Suction upstream model or suction plate
- Tangential blowing
- Symmetry

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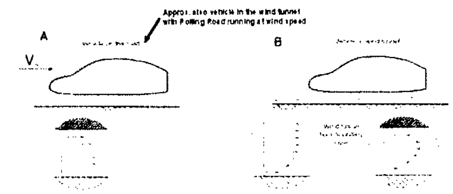
AEROSPACE TECHNOLOGIES OF THE 21st CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

GENERIC SHAPE OF BOUNDARY LAYER AROUND A VEHICLE



Ref. J. Katz: „RACE CAR AERODYNAMICS", 1995, Publisher Robert Bentley, Inc

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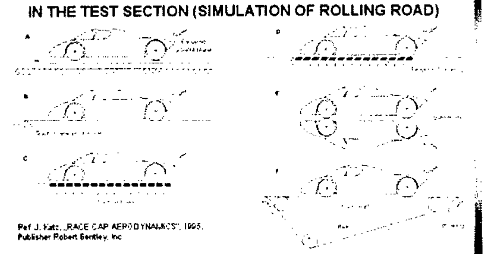
AEROSPACE TECHNOLOGIES OF THE 21st CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

VARIOUS METHODS OF FLOOR BOUNDARY LAYER CONTROL IN THE TEST SECTION (SIMULATION OF ROLLING ROAD)



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AEROSPACE TECHNOLOGIES OF THE 21st CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

FLOOR BOUNDARY LAYER CONTROL OF TEST SECTION

FORMULA 1 WIND TUNNELS

A) Primary (Scoop, Ramp) and secondary suction system

B) Rolling Road System (RRS):

- RRS typically built in turn table
- Polymeric or steel belt
- Suction below belt to prevent uplift due to vehicle underbody depression
- Auto tensioning and high accuracy tracking of belt (better than ± 1 mm)
- Maximum speed more than 70 m/s (accuracy < |± 0.1%| of actual velocity)
- Belt surface temperature control better than ± 0.5°C of air flow temperature
- Measuring of wheel lift forces through the belt

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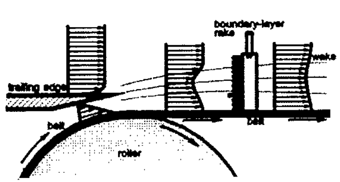
AEROSPACE TECHNOLOGIES OF THE 21st CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

ROLLING ROAD BOUNDARY LAYER DEVELOPMENT



Mixing of boundary layers at the trailing edge of the perforated plate and formation of the wake

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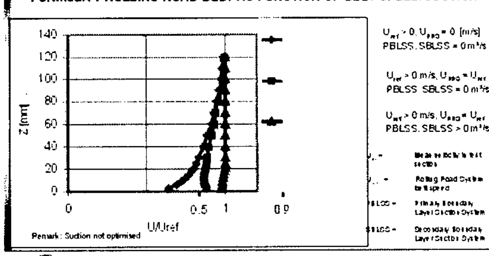
AEROSPACE TECHNOLOGIES OF THE 21st CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

TYPICAL FLOOR BOUNDARY LAYER PROFILES ABOVE THE MIDDLE OF A FORMULA 1 ROLLING ROAD BELT AS FUNCTION OF BELT SPEED/SUCTION



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AEROSPACE TECHNOLOGIES OF THE 21st CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

MODEL MEASURING TECHNIQUES

- Highly sophisticated carbon fibre models with independently fixed wheels running on the Rolling Road Belt (aerodynamic interference testing)
- Static pressure distribution on body and wings
- 6-Component overhead balance with model motion system (measuring accuracy better than 0.03% of full scale range; with aeronautical wind tunnels best about 0.01%
- 6-Component internal balance (measuring accuracy better than 0.1 to 0.2% of full scale range)
- Force and displacement measurements on different model components

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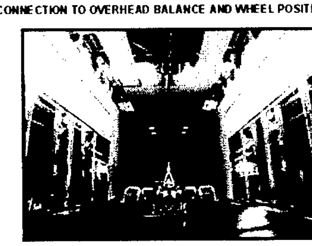
AEROSPACE TECHNOLOGIES OF THE 21st CENTURY
NEW TECHNOLOGIES OF EXPERIMENTAL RESEARCH AND SIMULATION

50% F1-MODEL IN TEST SECTION OF FERRARI F1 WIND TUNNEL

MODEL CONNECTION TO OVERHEAD BALANCE AND WHEEL POSITIONING DEVICES



TLT

Warren BEAULIEU

Mr. Beaulieu received his BS in Aeronautical Engineering from St. Louis University. He is currently a Principal Investigator for the development of low-density plasma technology applied to improving aerodynamic characteristic of aircraft and missiles. During the last four years he has been working with and coordinating this technology with various Russian institutes. His specialty is in aerodynamic propulsion systems with emphasis on inlet design and analysis of supersonic and hypersonic aircraft. Previous experience includes planning and conducting wind tunnel and flight test of aircraft propulsion systems.

BOEING®

WIND TUNNEL TESTING OF BLUNT BODIES IN WEAKLY IONIZED PLASMA TO DETERMINE AERODYNAMIC EFFECTS

Russian experiments in the past twenty years and, more recently, experiments In the US reveal that Weakly Ionized Nonequilibrium Plasma (WINP) in high speed flows causes various anomalous effects. Weakly ionized plasma over blunt bodies in supersonic flows has shown that there is an increase in the «speed of sound,» shock dispersion and shock strength attenuation, with an associated reduction in drag and heat flux. The weakly ionized plasmas, as a result of nonequilibrium relaxation processes, may modify flow parameters such as specific heat ratio, coefficients of thermal conductivity and second coefficient of viscosity

Boeing has been funding an effort to study weakly ionized plasma technology with the support of several Russian Institutes. The resulting wind tunnel testing in Russia has resulted in a better understanding of the thermo-physical processes of WINP and the ability to assess and quantify the aerodynamic benefits ofWINPs in high-speed flows.

This effort included testing at TsNIIMASH, TsAGI, ITAM and St. Petersburg University and the use of diagnostic equipment developed by the University of Moscow to measure critical parameters in the plasma field, Plasma generators used to demonstrate the effect of plasma in high-speed airflows include electrodes (anode-cathode), high frequency (Tesia) coils and microwaves. The structure of the plasma (plasmoid) were different from one plasma generator to another, and the degree of drag reduction and other aerodynamic benefits that were attained depended on the plasma generator employed. The power supply used for the plasma generators varied from direct current, alternating currents (AC/DC), high frequency and pulsed high frequency.

The wind tunnel testing showed significant drag reduction of up to 20 percent with relatively low levels of input power. Values for the propulsion effectiveness parameter were obtained as high as twelve. Also, testing at IVTAN demonstrated that weakly ionized plasma mixed with jet nozzle exhaust flow reduced the acoustic noise level.

Objectives of The Boeing Company For Funding Russian Wind Tunnel Testing

- Demonstrate and Quantify the plasma effect on aerodynamic bodies
- Establish data base for further research
- Gain experience in generation and understanding the physics of weakly ionized non-equilibrium plasma, WINP

BOEING

What Are Plasmas and Why Are They Important?

- Plasmas are ionized gases, (fourth state of matter).
- They occur in astrophysics, welding electrical discharges, lightening and other natural processes such as re-entry.
- Re-entry plasmas are "hot" in that the ion temperature is high.
- Weakly ionized (low ion concentration) "cold plasmas" have
  - ambient ion atom temperatures
  - significant high electron temperatures

The Russians have shown that cold plasmas can produce substantial aerodynamic benefits.

BOEING

Wind Tunnel Testing In Russia

- TSNIIMASH - Large scale conic forebody
- St. Petersburg University - Microwave generation of plasma
- TsAGI testing conic forebody models with various plasma generators
- ITAM plasma jet generator at M 2, 4, & 6
- IVTAN - Plasma to reduce acoustic noise from jet nozzle

BOEING

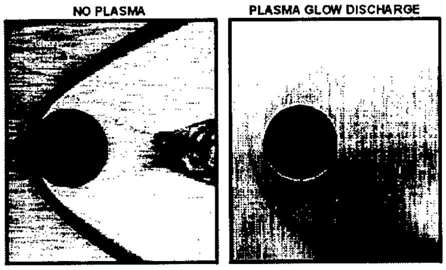
Benefits of Weakly Ionized Non-Equilibrium Plasma (WINP) Around High-Speed Aircraft

- Reduction of Wave Drag (up to 20%) at M=0.8 to 6.0
- Change of Wing Lift Force by 50% at M=0.8 to 2.5
- Bow Shock Wave Dissipation and Attenuation (≥10 Times)
- 4 to 6 Times Reduction of Heat Flux at Hypersonic Speeds at M=6 to 11
- Enhance Scramjet Combustion
- Reduce Acoustic Nozzle Exhaust Noise

BOEING

Ballistic Range

NO PLASMA | PLASMA GLOW DISCHARGE



BOEING 6

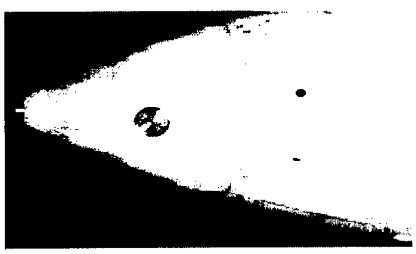
TSNIIMASH Testing

Objectives

- **Verify plasma generators operation : plasma jet and high frequency generators**
- **Verify plasma effect of drag reduction and shock attenuation**
  - **Force balance**
  - **Surface pressures**
  - **Schlieren videos**
- **Develop techniques for steady-state and dynamic pressure measurements (filter out plasma electrical effects)**
- **Measure pressures on model surface and base area**
- **Measure skin friction on model surface (preston tube)**
- **Measure model surface temperatures**

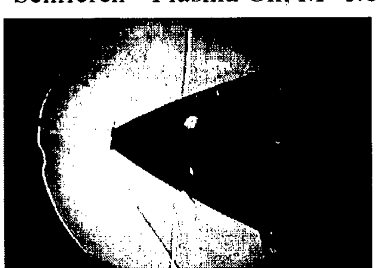
BOEING 1

Plasma Jets on Sides and In the Nose



BOEING 3

Schlieren - Plasma On, M=1.8



BOEING 2

Microwave Generation of Plasma

St. Petersburg University

PURPOSE:

Provide demonstration of plasma effect using a Microwave Generator

WHEN AND WHERE:

St. Petersburg University, 20-24 October 1997

ATTENDEES:

NASA Langley (1), BNA (2), RSC (2), NASA Dryden (2)

BOEING 4

TSNIIMASH Testing Conic Model

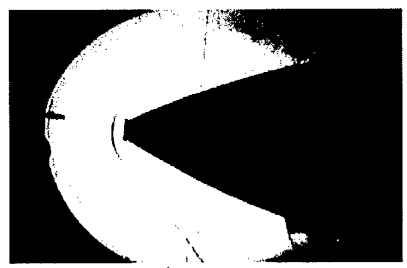
BOEING 1

Model Instrumentation

- **3 Preston Skin Friction Probes**
- **5 Dynamic Pressures**
- **56 Steady-State Pressures on Model Surface on Model Surface**
- **2 Internal Model Pressures for Reference Pressure**
- **2 Thermo Couples**
- **10 Thermal Strips (Max Temp Indication)**
- **Model Balance: Lift, Drag and Pitching Moment**

BOEING 2

Schlieren - Plasma Off, M=1.8



BOEING 1

Main Experimental Results

- **Large model was designed, manufactured and tested in plasma aerodynamic experiment for the first time**
- **Stable operations of all PGs of the model were realized in wind tunnel experiment at the following condition**
  - **M-1.8**
  - **Ps = 7-100 torr**
  - **a = -5°, 0, +5°**
- **Erosion of model surface was very small**
- **Aerodynamic characteristics (such as drag, lift and moments) and pressure distribution were measured in wind tunnel experiment simultaneously**
  - **Decrease of drag** <10%
  - **Maximum decrease of surface pressure** -3%, at a = 0; ~9%, at a = +5°
  - **Maximum decrease of total pressure, measured by Preston tube** ~10%
  - **Temperature, measured by thermocouple** ~ΔT=20K
  - **Temperature, measured by film sensor** ~ΔT=90-190K
  - **Increase base pressure** <20%

BOEING 3

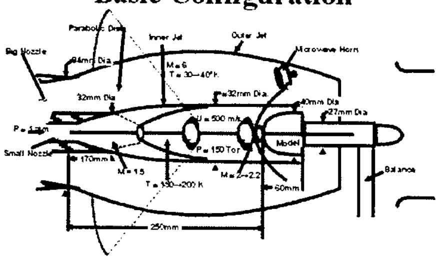
Microwave Testing at St. Petersburg University

Wind Tunnel Testing Conditions

Mach Number	1.7 - 2.0
Static Pressure	100 Torr
Diameter of AD Model (various shapes on balance)	40-50 mm
Frequency of Exciting Wave	3 GHz
Kind of MW Discharge	Free Localized
Operation Mode of Discharge	Pulse Repetition
Pulse Duration	1-10 μ sec
Repetition Rate	Up to 10 kHz
Mean Power of MW Discharge	Up to 3 kW
Pulse Power	Up to 200 kW

BOEING 5

Basic Configuration

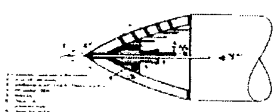


Microwave Test Set-up In Free-jet Tunnel

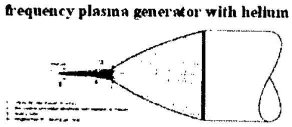
Results of Microwave Test St. Petersburg, Oct. 1998

- Successfully demonstrated that a stationary plasma flow field could be generated by microwave in Mach 2 flow
- Threshold for flow breakdown not much more than for static gas
- Drag reduction due to plasma flow field ranged from 1 to 9%
- Drag reduction was achieve with only 250 watts of input power
- Global gas temperature was increased by microwave not more than 30 Kelvin
- Stagnation pressure measured by high response transducers showed a reduction of 3 to 10%
- Plasma field needed to be in front of bow shock to cause a drag reduction

Schematic Plasma Generators



High frequency plasma generator with helium ejection

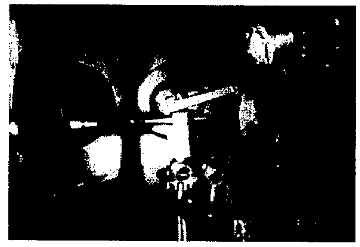


Electrode plasma generator with helium ejection

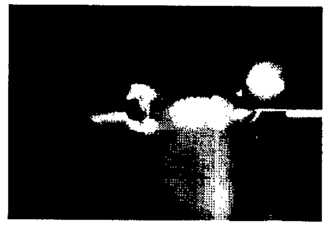
Summary of Plasma Generator Optimization and Wind Tunnel Test of 60 mm Models

- Five types of plasma generators were designed, fabricated and tested
- Plasma generators located on model successfully created a stable electrical discharge (plasma) in front of the bow shock at Mach 2
- Balance data, surface pressure distribution, probes and spectroscopic diagnostic results were obtained
- Drag data show:
  - Average drag reduction 3 to 6 percent from balance (low response)
  - Up to 30% drag reduction from surface static pressure (high response)
  - Up to 20% decrease in stagnation pressure from skin friction tubes
  - Significant change in bow shock wave shape
  - Power was limited to only 6K watts
  - Electrical interference (EMI) eliminated from test data
- Initial experimental data for scaling laws have been collected

Microwave Plasma Generated in Free-jet Tunnel



Microwave Plasma Generation in Front of Sphere Mach 1.8



PLASMA GENERATOR OPTIMIZATION WIND TUNNEL TESTING

TsAGI - Tunnel T-113

HF Plasma Generator

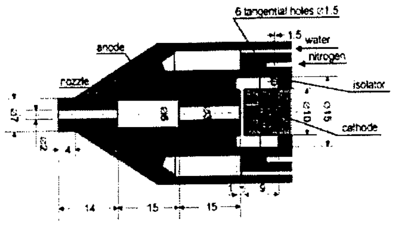
HF plasma generator

Model during assemble

ITAM Institute of Theoretical & Applied Mechanics Siberian Division

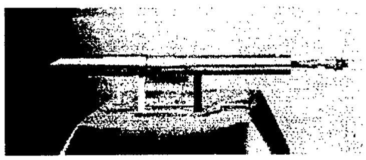
Investigation of Plasma Jets at High Mach Numbers: 2, 4, 6

Drawing of Plasma Jet Generator



3

Photo of PG mated with Strain Gage Balance

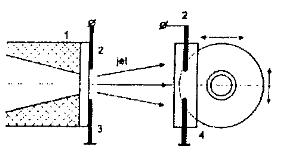


5

IVTAN Test
Plasma To Reduce Acoustic Noise From Jet Nozzle

2

Schematic of Plasma Electrodes



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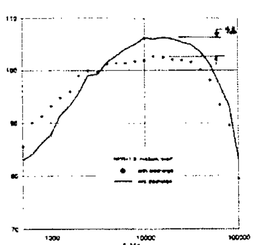
Test Results

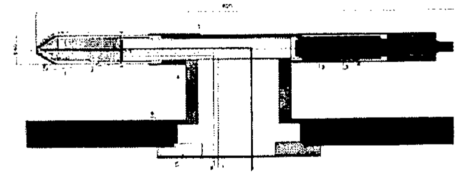
4 db Peak attenuation



A/C discharge, 6 cm from jet axis, 10 cm from nozzle, NPR = 1.9

6

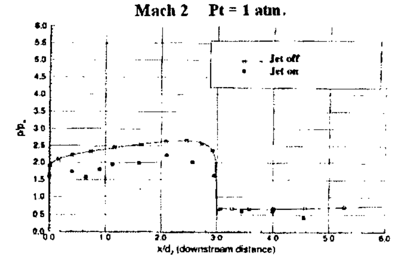
Model Installation mated with Strain Gage Balance



4

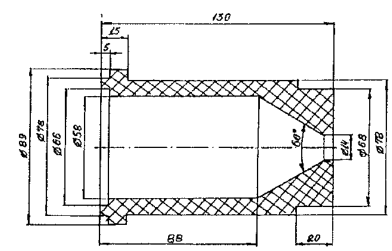
Surface Pressure Distribution ITAM Truncated Cone-Cylinder

Mach 2 Pt = 1 atm.

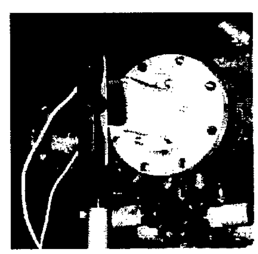


1

Nozzle Geometry



Test Set-up "Dusty" Plasma Generated From Electrodes



5

Results of Russian Funding

- Objectives of The Boeing Company were met
  - Demonstration of drag reduction using plasma
  - Obtained data base for several different types of plasma generators
  - Knowledge gained in understanding the physics of WINP and its generation
- Developed beneficial working relationship with Russian Institutes

7

Hervé QUINIOU

1985 – 1988 Snecma Compressor Aerodynamic DepartmentCFD Specialist responsible for flutter prediction methodes (Unsteady Quasi 3D and 3D Euler codes)
1988 – 1992 Snecma Compressor Aerodynamic Department Aerodynamic Design Manager in charge of commercial fan & LP compressor design
1992 – 1996 Snecma Compressor Aerodynamic Department Aerodynamic Design Manager in charge of commercial and military compressor design
1996 – 2000 Snecma Compressor Aerodynamic Department Manager responsible for designand research activities in compressor aerodynamics

snecma

COMPRESSOR DESIGN BASED ON INTENSIVE USE OF CFD METHODS

Abstract

Computational Fluid Dynamics (CFD) tools represent a significant source of improvement in the design process of turbomachines, aiming to better performances, lower costs and associated risks.

Snecma compressor design process rely intensively on CFD methods. In the 80s, the use of 3D Euler methods was the cornerstone of commercial fan design methodology meeting high level of efficiency. In the early 90s, 3D Navier-Stokes solver and unsteady 3D Euler solvers were introduced in design process. Hundreds of 3D Navier-Stokes calculations were run before the release of a compressor or a turbine.

Numerical models are constantly improved to account for real geometry and include various technological effects (tip clearances, fillet radii, flowpath alignment, bleeds, cooling flows,...) and multi stage simulations. This means to implement more complex turbulence models, transition simulation and to modelize unsteady phenomena

This paper illustrates the effort made by Snecma to adapt these methods to design process following three pathes :

- Simulation improvment
- CFD methods validation / calibration
- Adaptation to designer environment ("ready to use" methods)

It will show some examples of applications of this design process.

Key words: Turbomachinery – Computational Fluid Dynamics – Compressible Turbulent Flow

1. Introduction

The design of advanced aero-engine fans and compressors has to meet ever more demanding requirements. Higher performance must be achieved within shorter design cycles and at lower cost. Ambitious objectives in the reduction of weight, complexity and manufacturing costs lead to fewer compressor stages, and therefore to increased stage loadings.

For compressor designers, this new situation implies the capability to control the very complex flow phenomena occurring in highly loaded stages, on the whole operating range of the compressor, early in the program. In addition to aerodynamic performance, the aggressive design of advanced, fully 3D blades also requires an early focus on all the aspects related to engine mechanical integrity: blade flutter and forced response as examples.

Up to the end of the 70's, most of the design and optimization process relied on an empirical approach, which meant a very large number of tests. The all-experimental optimization strategy was very time and cost consuming for two reasons at least. Each iteration implied all the phases from design to manufacturing, instrumentation and testing. Secondly, determining what had to be improved in the design required a comprehensive instrumentation on real engine components, which was strongly limited by technological constraints. As a result, it was very difficult to identify the potential problems and even more difficult to understand them.

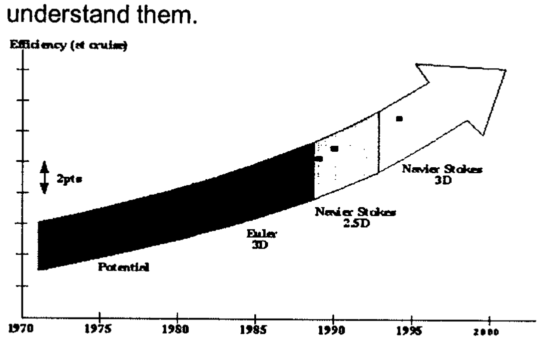


Figure 1: Impact of CFD on Snecma Commercial Fan Performance

For these reasons, SNECMA started very early to take advantage of the fast-growing computer power and of the concurrent advances in Computational Fluid Dynamics. This approach has been greatly rewarded as the introduction of CFD tools in the design methodology has brought major improvements in the iterative optimization process of fans and compressors. For example, the impressive re

sults obtained on fan design (Figure 1) within a relatively short time, have demonstrated that the use of CFD is a successful tool to achieve continuous improvements in aerodynamic performance, and also to shorten design time scales and reduce cost.

An attempt to summarize this contribution could use the following keywords: faster response, broader range of alternative solutions, better description of flow complexity. Indeed, every computation node in a numerical simulation is also a «measurement» node, which allows an easy and comprehensive analysis of the flow prediction.

Unfortunately, CFD is still far from faithfully reproducing reality. Even with the power of the most recent super computers, simulation capabilities still depend on very approximate physical models or are limited to component parts. The computation of a full multistage high pressure compressor with 3D, unsteady and viscous, small scale phenomena is out of reach for a long time yet. As a result, the major challenge for both the engine component designer and the CFD method developer consists in integrating new computational methods, with their capabilities and limitations, in the design process in a fast, safe and efficient way. Every new method brings new answers, but also raises new questions. The most obvious risks in using a new, more powerful tool are either misunderstanding or overoptimistic confidence in the results.

A constant effort must therefore be dedicated to the comparison, validation and calibration of methods. This means in particular that heavily instrumented rigs, representative of real engine flows be used to produce an appropriate validation data-base.

At SNECMA, a strong interaction between compressor designers and CFD tool developers has always allowed an early use of advanced methods in the design process: 3D Euler in 1984, Quasi-3D Navier-Stokes in 1988, 3D Navier-Stokes in 1992. The recent development of parallel vector computing and workstation network now makes possible the use of multistage 3D Navier-Stokes in the design process of multistage compressors. Most of those recent CFD developments have been undertaken in close co-operation with research laboratories such as ONERA, LEMFI (University of Paris VI) and Ecole Centrale de Lyon.

This paper brings up the aerodynamic design and analysis process of turbomachines at SNECMA. Since design methodology has been presented several times, this paper will be focused on analysis tools which are described with a particular emphasis on the numerical basis of currently used CFD codes and on the combined efforts to develop homogeneous and user friendly pre and post-processors.

2. Evolution of Compressor and Turbine Analysis Tools

The efficient integration of new computational tools with increased simulation capabilities is a real challenge for the designer. To take advantage of the fast advances in CFD developments, the design methodology and procedure must be constantly adapted according to new simulation capabilities. Improvements have therefore been brought to the methodology presented by Falchetti[1], Brochet[2] and Vuillez[3]. All these papers already pointed out the importance of CFD methods and the improvements they can bring to the design of fans and compressors. As an example, the fan of the CFM56-5C which powers the Airbus A340 was designed using 3D Euler and Quasi-3D Navier-Stokes solvers whereas the CFM56-7 large chord fan design for the latest Boeing 737 family is based on 3D Navier-Stokes calculations. The demonstrated outstanding performance achieved by this recent design shows that the use of CFD is not only an excellent tool to improve efficiency but also to shorten time scales and reduce costs.

A major new step has recently been introduced in the blade analysis phase by accounting for technological effects such as radius fillets, rotor tip clearances or buttons of variable-stagger stator vanes. The current full 3D Navier-Stokes code is now capable of predicting the main consequences of these effects which are considered to be significant in the matching of high pressure compressor stages. From a practical point of view, the level of consistency achieved between 3D calculations and throughflow objectives is driven by the industrial know-how based on past experience. The discrepancy observed between 3D and throughflow models highlights the limitations of the classical approach which splits the real flow in two two-dimensional flows called S1 (blade to blade) and S2 (hub to casing). The steady multi-stage 3D Navier-Stokes code introduces a major change in the design process since it is no longer necessary to prescribe aerodynamic conditions from the throughflow model at the interface between blade rows. This new multi-stage tool is now fully integrated into the design methodology even though the analysis of a new design is always initiated using single blade row calculations. As a matter of fact, it appears to be more efficient to initiate the design with rapid calculations and ultimately to check the whole compressor operation with more elaborate tools such as the multi-stage code.

The use of advanced tools allows the designer to enhance the inlet specific flow of fans and to increase the mean stage loading of compressors and turbine while ensuring adequate stability margins.

3. Description of Analysis Tools

3.1 Navier-Stokes Solvers

In the 70"s and early 80"s, because of computer power limitations, industrial users had to develop specific CFD codes to solve the various problems they had to face. CPU time and memory considerations needed a deep optimization of software

coding. This lead to a set of tools that had their own numerical scheme, pre and post processing.

In the late 80"s and early 90"s, outstanding develoment of computer technology and progress made in numerical techniques made possible a large number of new CFD applications. More and more sophisticated methods became available for industry: 2D or 3D, viscous or inviscid, steady or unsteady codes. On the other hand, growing computer capability allowed a more global optimization of development of CFD codes regarding not only CPU time performances but also codes development and support costs which must be kept at an affordable level. All applications were supposed to take credit from the work on any of them in order to save time and money.

At Snecma, two types of Navier-Stokes solver are currently used:

ONERA's CANARI solver

LEMFI's Turbo3D

ONERA's CANARI is a compressible, finite volume, time marching, multi-domain code solving full Navier-Stokes equations on a structured grid. The numerical core is based on a four step Runge Kutta explicit scheme combined to Jameson and Turkel second and fourth order numerical dissipation model. On top of this scheme, residual are smoothed by an implicit technique developped by Lerat.[4,5]

Turbulent closure of the Reynolds averaged Navier-Stokes equations is obtained using different turbulence models – Michel's[6] or Baldwin-Lomax[7] algebraic models, Spallart-Almaras[8] one-equation-model, k-ε two-equations-model. The use of algebraic turbulence model is a good compromise between code robustness, acceptable accuracy and computing costs and elapsed time even if the extension of such models for 3D applications requires special care.

All boundary conditions are imposed through compatibility relations.

To minimize cost of ownership of these different methods, the different CFD tools such as 3D Euler and quasi 3D Navier-Stokes share the same numerical core. As shown later, multi-domain approach has been widely used for multi-stage applications.

In spite of very succesful design based on the intensive use of CANARI, higher accuracy turbulent solvers were needed to account for severe «aerodynamic constraints» (such as 3D effects, pressure gradient,...) or unsteady effects. Developed by the Fluid Mechanics Research Laboratory (LEMFI) of CNRS for Rotor/Stator simulations ("Forced response project"), the TURBO3D code solves the compressible Favre-averaged Navier-Stokes equations, with a closure of the turbulence terms proposed by Launder & Spalding for incompressible flow with two transport equations for k, the turbulent kinetic energy and ε, its dissipation rate. This "high-Reynolds" model is appropriate to the freestream (away from wall). In order to deal with boundary layers, the constant of the model can be modified to take into account the eddy viscosity near the wall. This leads to a "low Reynolds" model. The Launder-Sharma[9] near-wall k-ε turbulence closure is used in the code to deal with the semi-empirical transport of the modified dissipation rate ε.

The numerical method of the code is described in detail by Vallet[10,11]. The mean-flow and turbulence transport equations are expressed into the cartesian coordinate rotating frame and are discretized in space, on a structured grid, using a 3rd order upwind-biased MUSCL scheme and Van Leer flux vector splitting with Van Albada limiters. The resulting semi-discrete scheme is integrated in time using a 1st order implicit procedure. The resulting scheme is highly robust and efficient.

With the latest code developments (CANARI & TURBO3D) and the new computer languages ("Object Oriented Languages, Internet Technology,..."), the scheduling of a new "Multi Purpose & Multi Environment" CFD platform becomes a reality. The ONERA CFD project named "elsA" (for "Ensemble Logiciel de Simulation en Aerodynamique") will meet the industrial needs: a new modular, flexible and scalable structure. ElsA will enable us to integrate different solvers from different research teams in order to obtain the most cost-efficient simulation for a complex problem. With this kind of tool, the simulation of a new complex problem will look like a modular and extensible construction assembly game: the assembly of different modules (the most appropriate modules for a given problem) to perform the complete simulation.

3.2 Pre and Post Processing Tools

A high quality modular solver is not sufficient to obtain industrial-grade CFD tools. Fast and precise simulation tools are not much helpful if the time and man-power required to build the simulation test case and to analyze it is too important.

Due to the simplicity and repeatability of the compressor geometry, the benefits of structured multiblock meshes can be fully exploited: simple algorithms, easy coding,... As a result, SNECMA has been able to develop its own dedicated mesh generator and associated pre-processing. This mesh generator is based on few "external parameters" (less than one hundred) which can be "graphically" modified to obtain an "optimal" (in terms of quality) mesh. Then, the "batch" version generates one million mesh points for a single blade 3D Navier-Stokes grid in less than one minute on standard Silicon Graphics workstations.

To account for technological effects – such as radius fillets- additional processing is performed on the standard mesh. To guarantee future demands and evolution those tools have been developed using "Object-Oriented Languages". Additional functionality – as by-pass flow separator, mid-span shroud – are implemented by merging different standard meshes.

Finally, the aim of pre-processing is to collect data and requirements from the mesh generator, throughflow computations, and user demands, to define the input grid and boundary conditions of the solver and the aerodynamic input. Initialization is directly provided by throughflow data for steady computations, then altered as needed to account for boundary layers developing at end-walls. Additional inputs are taken into account for unsteady calculations, like blade vibration modes for flutter simulation for instance.

To be efficient, post-processing tools must offer several levels of investigation. A straightforward, batch tool is necessary to obtain reduced data, providing fast answers even from heavy 3D Navier-Stokes computations. This is particularly convenient in parametric studies around a configuration close to the final one. It provides spanwise distribution of standard flow quantities, or pressure distribution on blade profiles. But a deeper and interactive investigation may be necessary, with strong 3D visualization capabilities. At SNECMA, the solution consists in the combination of in-house, modular tools specific to turbomachinery applications and of 3D visualization software from vendors.

4. Application of Analysis Tools to the Prediction of Turbomachine Performance

4.1 Technological Effects

For the design of multi-stage high radius ratio such as core compressor or high pressure turbine, it is very important to account for technological effects such as tip clearance, flowpath misalignment, bleed flows or cooling flows. All these parameters affect widely stage performances (flow and efficiency) and therefore the whole loading stagewise distribution. If not well anticipated, they may lead to severe stage mismatching inducing performance penalty (all the stages do not reach high efficiency at the same compressor operating point) or operability defects in the case of a compressor.

Figure 2 shows different secondary flows that are to be accounted for during a cooled turbine design. Tip clearance vortices, cooling flows upstream turbine nozzle throat can impact severely turbine flow function and loading. The consequences of this are not limited to turbine performances (efficiency, life) but affect also compressor operating line which can shift off-design and therefore provide poorer flow or efficiency or even unacceptable stall margin jeopardizing engine operability

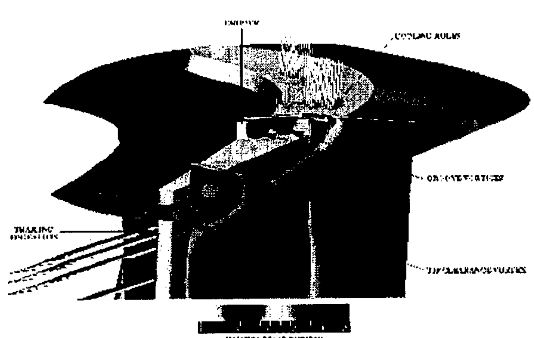


Figure 2: Technological Effects in a Cooled Turbine

As detailed in referenced paper[12], CANARI code is able to predict flow trends induced by flowpath discontinuity. During the tests of a single stage research compressor, flow measurements were carried out at blade and vane exit. 3D Navier-Stokes simulations (run using CANARI code) on the rotor blade were in good agreement with traverses. Downstream stator vane unexpected discrepancies were found between test data and flow simulation.

As shown on figure 3 a region of high pressure losses can be identified behind the stator vanes on a substantial portion of the annulus toward the outer annulus. This corner flow separation could not be reproduced by 3D Navier-Stokes computations of the stator vanes. Following the test results, a close examination of the ECL4 geometry revealed that the buttons of the variable stator vanes were slightly out of line with the flowpath, by a value of about 0.3 mm which amounts to 0.5% of vane height (Figure 4).

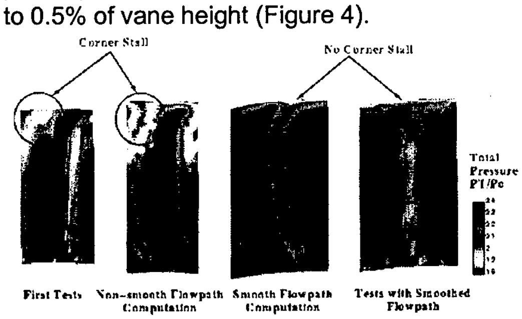


Figure 3: Compressor Variable Stagger Vanes - Experiment VS Computation Comparison

Figure 4: Compressor Variable Stagger Vanes – Button Misalignment

As detailed by Escuret[12], using a simple numerical approach to account for the actual geometric discontinuity of the annulus, the "CANARI" computation then showed flow trends similar to that of the experiment. Also, a detailed analysis of the computed flow field indicated that the flow turning (in both the radial and tangential directions) due to the button blockage contributed toward strengthening the effect of secondary flows. Subsequently, after the geometry of the VSV buttons was corrected to match the flowpath, further tests confirmed a much more satisfactory flow behav-

ior leading to a one-point improvement in overall compressor adiabatic efficiency.

4.2 Multiple Blade Row Calculations

With the recent increase in computational power, the compressor designer is no longer restricted to the analysis of an isolated blade row when using 3D Navier-Stokes computations. It is now possible to consider multiple blade row configurations to take into account the influence of adjacent blade rows[13] and to predict the development of endwall losses across the compressor, provided that some simplifying assumptions are made so as to perform a steady computation.

Two different approaches currently used at SNECMA for the coupling of blade rows are presented in this paper:

- the mixing plane approach
- the deterministic stress approach

4.2.1 Mixing Plane Approach

In this simple approach, the tangential averages (in the stationary frame of reference) of flow quantities at one side of the interface plane between adjacent blade rows are used to update the numerical scheme values on the other side of the interface plane. The precise choice of the physical flow properties to be averaged and exchanged across the interface plane is not a trivial matter as there is no such average flow that would satisfy all the conservation equations at the same time. A simple solution is to use primitive flow variables, replacing the internal energy by the static pressure: r, rV_x, rV_r, ρV_t, p, k, ε. Another widely used approach is to use conservative flow variables, i.e. ρV_x, ρV_x+p, ρV_xV_r, ρV_xV_t, ρV_xH. A third approach is to favor the continuity of the entropy flux over that of ρV_x+p. Whatever solution is used, a natural effect of the mixing plane approach is that the average of some physical flow properties are discontinuous across the interface plane between adjacent bladerows.

4.2.2 Deterministic Stress Approach

Easy to implement and cost effective, mixing plane approach does not simulate accurately flow disturbances coming from adjacent rows such as wakes, shocks or potential pressure fields and their unsteady interactions.

An approach first exposed by Adamczyk[14], proposes to account for the "average" contribution of the temporal and passage-to-passage flow perturbations in a steady, periodic from blade passage to blade passage, multi-stage flow model (figure 5): the so-called "average-passage" flow equation system. Although the derivation of this model is mathematically rigorous, its interest is practically limited by the difficult task of estimating the new terms in the equation system, i.e. the "deterministic stresses".

A simplified approach proposed by Rhie[15], neglects the passage-to-passage flow variations and calculates the values of the deterministic stress terms using a steady representation of blade row

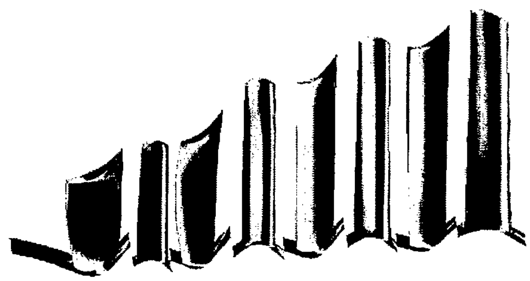


Figure 5: Commercial LP Turbine - Multi-Stage Calculation - Mixing Plane Approach

interaction. This approach has recently been introduced in the CANARI code under a collaborative research project with Ecole Centrale Lyon, ONERA, TURBOMECA and SNECMA. As illustrated on Figure 6 for the case of a subsonic compressor stage, the deterministic stresses are calculated using spatial (i.e. tangential) averages on overlapping meshes where axi-symmetric body-forces have been applied to account for the potential effect between closely coupled rows. During the computation, both the deterministic stress terms and the body forces are exchanged from one blade computational domain to the other.

Although it is more CPU expensive than the mixing plane approach, this approach presents some

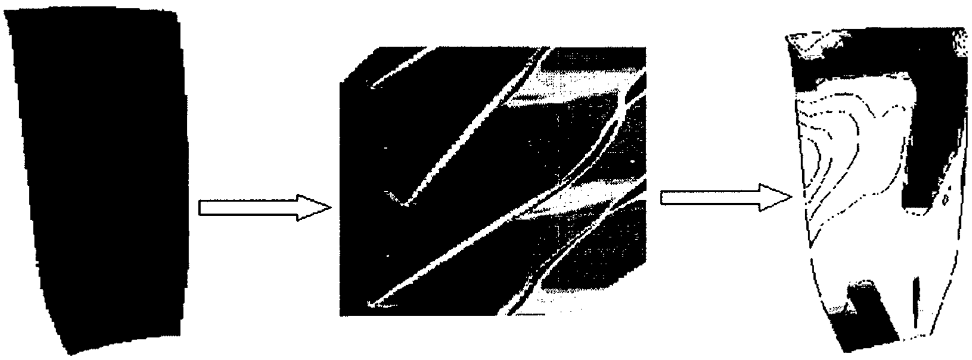
Figure 6: HP Compressor Stage - Multi-Stage Calculation - Deterministic Stresses Approach (Rhie)

valuable advantages. It is a continuous interface plane approach as, by definition, the contribution of deterministic stresses restores the continuity of tangentially-averaged flow properties across interface planes. Moreover, it simulates the average wake blockage and the steady mixing effects which are believed to be of primary importance for the matching of blade rows at off-design conditions. However, purely unsteady effects such as wake or shock wave chopping by neighboring blade rows (i.e. unsteady mixing effects) are clearly neglected.

5. Unsteady Analysis

5.1 Blade Flutter Prediction

Blade flutter is a major concern for the safety of compressor operation. It is induced by an unstable coupling between the blade eigenmodes and the resulting fow unsteadiness. This phenomenon is well known on aircraft wings and helicopter blades. The origin of this excitation can be flow separation at the leading edge on suction side when a blade operates at high incidence and low rotational speed(subsonic flutter) or shock motion



a – Eigenmodes Analysis Displacement Distribution   b – Aerodynamic Unsteady Analysis   c – Aeordynamic Unsteady Analysis Mean Power Distribution (Red = Unstable)

Figure 7: Aerodynamic Unsteady Analisis

when inlet flow is supersonic (supersonic flutter). Another type of flutter can come from shock motion in a choked configuration (choke flutter)

5.1.1 Supersonic Flutter

To study supersonic flutter, a methodology has been set up based on mechanical analysis software and unsteady 3D Euler code. This process has been extensively brought up by Gerolymos[16] and Burgaud[17].

Vibrations analysis is carried-out on a whole-bladed disks accounting for cyclic symmetry, providing airfoil motion and eigenfrequencies. The resulting blade displacement distribution for a given mode is input in an unsteady 3D Euler code. The unsteady calculation (assuming chorochronicity) is performed on a single blade passage for different wave number. The unsteady pressure and motion are then time-integrated over a natural period to provide mean power distribution which is summed over the whole blade to yield the aerodynamic damping parameter.

This methodology has been validated on different research fan blades. It is a part of Snecma fan design process to anticipate any potential risk of supersonic flutter early in the project.

5.1.2 Subsonic Flutter

Unlike supersonic flutter, subsonic flutter involves strong viscous effects as it is characterized by an unsteady separation of the boundary layer on the blade suction surface near the leading edge. In consequence, it requires the use of unsteady Navier-Stokes computations with a turbulence model appropriate to the simulation of this complex flow phenomenon.

Figure 8: 2D Navier-Stokes – k-ε turbulence model - Mach number contours

The approach recently developed by SNECMA is based on a two equation k-ε turbulence model with a low Reynolds model near the wall. This approach is currently being validated against 2D cascade data representative of the tip section of a wide chord fan at part speed conditions (inlet Mach number of 0.7 and 6° positive incidence). Figure 8 shows the Mach number contours around the blade airfoil as computed by the 2D Navier-Stokes code with a k-ε turbulence model: a large flow separation initiates at the leading edge and extends over 10% of the airfoil chord on the suction surface. The real and imaginary parts of the unsteady static pressure coefficients on the airfoil suction and pressure sides are given in Figure 9 (case of a torsion mode at the frequency of 332 Hz and phase angle of 90°).

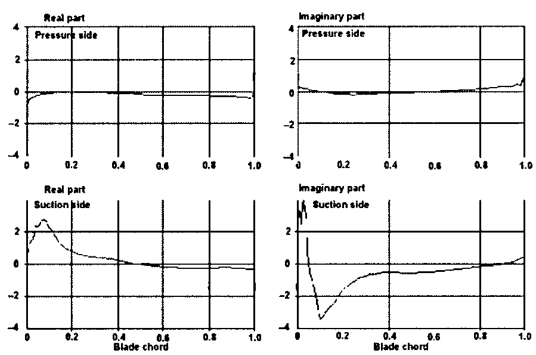


Figure 9: Unsteady Pressure Chordwise Distribution

The current approach taken by SNECMA is to use this newly developed numerical analysis in support of the available empirical criteria as the validity of these criteria is generally limited to the range of existing configurations.

5.2 Forced Response Analysis

Another source of fluid/structure interaction is the rotor/stator aerodynamic interaction. Each blade row is periodically impinged by the wakes coming from the upstream blade row(s) and submitted to potential or shock wave interactions from the downstream blade row(s). The usual procedure in blade and vane design consists in avoiding too close proximity between the frequencies of blade or vane vibrating modes and the forced excitation frequen-

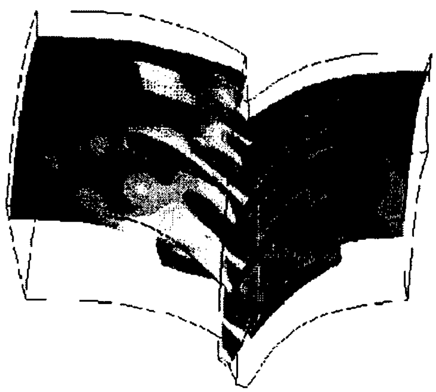


Figure 10: Computed flow field from unsteady 3D Euler code (IGV – Rotor 1 unsteady interaction at part speed)

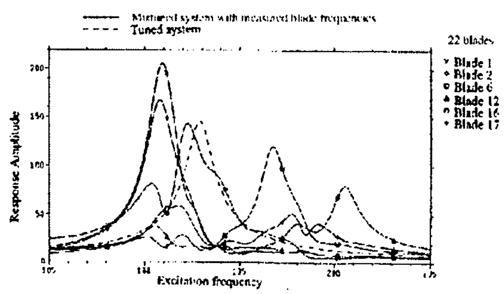


Figure 11: Mistuning influence on forced responses amplitude

cies linked to upstream and downstream blade rows, for rotation speeds corresponding to steady engine operation. This procedure is typically illustrated by the Campbell diagram representation[18].

In the case of most multi-stage compressors, however, it is next to impossible to avoid all crossings with the required frequency margin. The designer has therefore to make a choice between several non ideal configurations, mainly on the basis of prior empirical experience. But this is sometimes inconclusive or simply scarce. The approach developed at SNECMA is to provide help to the aero-mechanical designers in assessing how critical the potential frequency crossings are, by using unsteady computations[19].

5.3 Compressor Stability

In recent years, a large amount of work has been devoted to understanding the onset of stall and surge in axial multistage compressors. SNECMA actively took part in this research effort through a European collaborative project under the Brite-Euram program, in which four high speed compressors were tested to investigate the generic features of stall[20,21]. The measurements showed a very broad range of stall related disturbances. Both short lengthscale (spikes) and long lengthscale (modes) disturbances were detected in three out of the four compressors tested. A clear trend was observed with spikes appearing at low rotational speeds changing to modes in the mid-speed range (i.e. 80%÷90% of nominal speed). Moreover, stage matching was identified as one of the parameters which can bring about a change from one stalling pattern to the other[22]. Spike type stalling, a localized phenomenon, would seem to result from situations where individual blade rows are more highly loaded than the rest while modal type stall inception, a more global phenomenon, would rather occur when all stages are evenly matched at the stall onset point. At full speed, the growth of the stall cells was found to take place over fewer rotor revolutions than at lower operating speeds and the origins of the stall cells were not clearly identifiable in terms of modes and spikes. In the compressor with the highest pressure ratio, flow breakdown at full speed occurred so quickly that rotating stall could not be detected before the surge event. The symmetry of the flow throughout the entire compressor was disrupted in the space of one rotor revolution.

Regarding the problem of aerodynamic instabilities, the compressor designer is faced with the practically important but difficult task of quantitatively predicting the surge line. Until recently, this was performed by using exclusively empirical criteria on parameters such as diffusion factors, flow incidence on blades or static pressure rise on the endwalls, all obtained from an off-design throughflow calculation. Nowadays, the trend is to rely on new methods more representative of the flow physics but a numerical method capable of predicting the surge line on the basis of a theoretical model must include several features. Firstly, it must take into account the whole compression system, i.e. all parts involved in the compressor stability: the compressor itself, the downstream volume and the throttling device which controls the operating condition of the compressor. Secondly, boundary layer growth and separation on the compressor blades and endwalls must be modeled in a way which permits to accurately predict the compressor speedline at off-design conditions (in this point generally lies the accuracy of the method). Finally, it has to be an unsteady method in order to adequately reproduce the onset of the unstable phenomenon.

The simplest level of modeling which fits this description is a time-linearised method, with 1D fluid equations integrated over cells each comprising a blade row or a full stage[23]. Fluid perturbations in the compressor are then solutions of a linear system, the eigenvalues of which represent the damping or growth and frequency of these perturbations. Such a method is currently in use at SNECMA, integrated with a throughflow method to provide fast and reliable surge line predictions for HP compressors.

However, the method mentioned above is not adequate to deal with low hub-to-tip ratio machines or ones with strong flowpath curvature and radial variations. Moreover, it does not properly address the stall inception process in so far as it only ac

counts for axial instability modes (i.e. surge). A non-linear three dimensional method has therefore been developed at SNECMA[24,25] in order to simulate circumferential instability modes (i.e. rotating stall) as well as the non-linear coupling which is experimentally observed between rotating stall and surge. This method is based on a 3D unsteady Euler solution in blade free volumes which is dynamically coupled with a multiple through flow solution within blade rows (Figure 12). The blade row model is obtained from circumferentially averaged unsteady Euler equations so that blade effects are represented by two blade forces which are respectively perpendicular and parallel to the flow velocity. These blade terms are derived from steady-state blade row characteristics with a time lag approach (i.e. convection time) which considers the time required by boundary layers around blade profiles to adapt to varying inlet flow conditions. This code is capable of simulating the onset of long length scale rotating stall and is used to give a 3D picture of stall inception. Applied to a high speed four stage research compressor 20, the method reproduces well the time scales characteristic of instability development. In particular, it simulates the fast growth rate of instability at full speed, giving rise to a global compressor instability in less than 5 rotor revolutions (Figure 13).

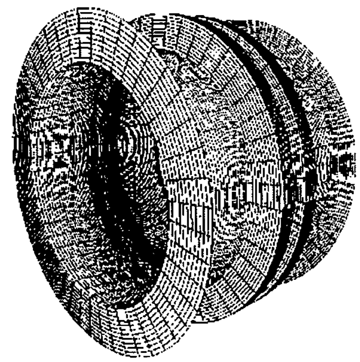


Figure 12: Description of 3D unsteady compressor model – Coupling of 3D Euler computations in blade-free volume. Multiple unsteady through flow solutions (tangentially uncoupled) in blade rows

The 3D stall model only accounts for blade passage effects at a macroscopic level through the use of loss and deviation correlations. As a result, it cannot reproduce the development of spike-type stall, an instability for which the actual flow phenomena within the blade passage (i.e. large flow separation, tip leakage) must be resolved20. This requires the use of unsteady 3D Navier-Stokes computations on numerous blade passages with a turbulence model capable of representing these complex flow phenomena. Although very consuming of computer power, this advanced numerical approach will soon be feasible, at least for single stage configurations.

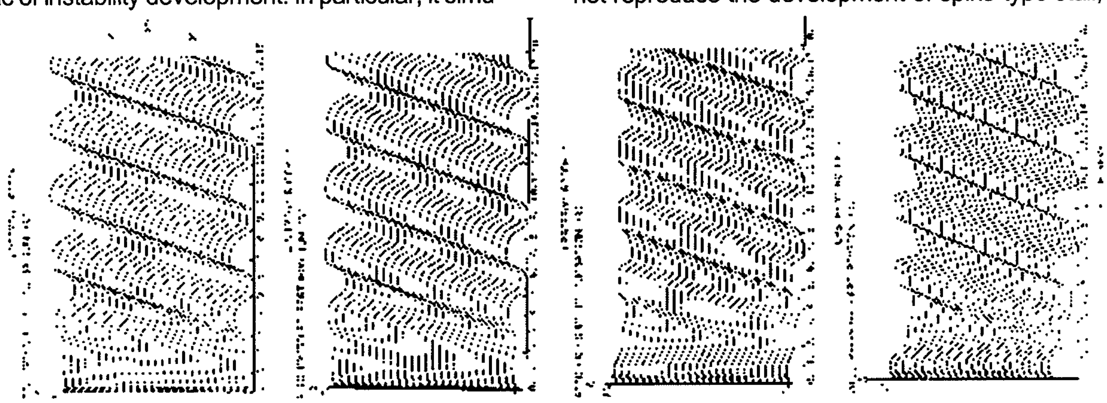


Figure 13: Computed Stall Cells Development in a four stage research compressor

6. Conclusions

This paper has presented the latest advances in the aerodynamic design and analysis process of fans and compressors at SNECMA. The main conclusions of the paper can be summarized as follows:

• The role of CFD in the design procedure is fast-growing. New tools have been developed allowing the treatment of numerous difficult problems as close as possible to the reality: tip clearance, technological effects, multistage effects, unsteady phenomena (forced response, aeroelastic and aerodynamic instabilities).

• A great effort is also dedicated to turn numerical methods into integrated tools which are easy to handle by designers. The aim is to create a « user friendly « environment to enable the designer to focus primarily on the physical analysis of numerical results.

• Experimental investigations of research compressors with a comprehensive and high quality set of measurements are essential to produce an appropriate database for the validation and calibration of advanced numerical methods.

The authors are strongly convinced that all these research efforts will provide a better understanding of the aerodynamic behavior of real aero-engine fans and multi-stage compressors. However, the integration of new analysis tools with improved simulation capabilities requires a permanent update of the design methodology in order to turn this knowledge into valuable gains to the final product.

It must be borne in mind that the ultimate objective of the design procedure is to improve the

compressor performance and at the same time to reduce costs and design cycles. Despite the recent breakthrough in CFD, highly skilled engineers specializing in the field of compressor aerodynamics are therefore still needed in order to reach these ambitious objectives.

Acknowledgements

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It must be emphasized that the results presented in this paper have been obtained by many coworkers in the Department and at SNECMA.

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HUNDRED YEARS OF LAMINAR WING TECHNOLOGY (history and status)

Dr. K. Haag, Dr. G Redeker

Abstract

The laminar flow technology and its development from the very first origins to a demonstration in flight test is presented as example for the „life cycle" of new technologies in Aeronautics.

The presentation gives a short overview over the basic scientific ideas and results and first tests on laminar flow technology in the first half of the 20th century. It then focuses on the research in DLR that started around 1980 becoming more and more an research field of European interest in 1990, describing the research strategy with the following major elements:

- Definition and validation of transition prediction for engineering purposes,
- Validation and demonstration of natural laminar flow technology,
- Validation and demonstration of hybrid laminar flow technology.

Introduction

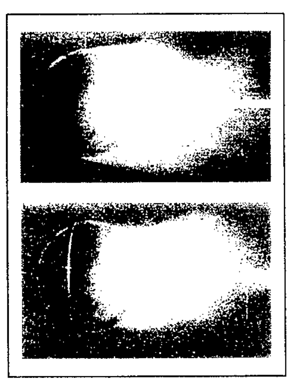
The research in laminar flow technology has a long history. The basic ideas and theories have been developed in the first half of the 20th century. Due to its potential of drag-reduction it has always been a research field at first for sailplanes or gliders and as will be shown later also for larger aircraft, but was sometimes overruled by other priority themes in the development of aircraft.

With the oil-crisis laminar flow technology became a topic of priority also for civil transport aircraft, because it is one of the most promising options for drag reduction, which leads to reduction in fuel consumption and consequently to a reduction of fuel costs. Therefore laminar flow technology can influence two major drivers of air transport business the profit situation of airlines and the price for a ticket, the customer has to pay.

Beside the economic argument there is another potential benefit that has to be taken into account- the greenhouse effect. The reduction of fuel consumption directly reduces the production of emissions.

Historical Overview

The research in laminar flow technology is based on Prandtl and his boundary layer theory from 1904. One famous experiment from 1914 done by Wieselsberger – the sphere tests with a tripping wire after Prandtl- showed that boundary layers can be laminar or turbulent (Figure 1). This and other



from H. Schlichting: Boundary Layer Theory

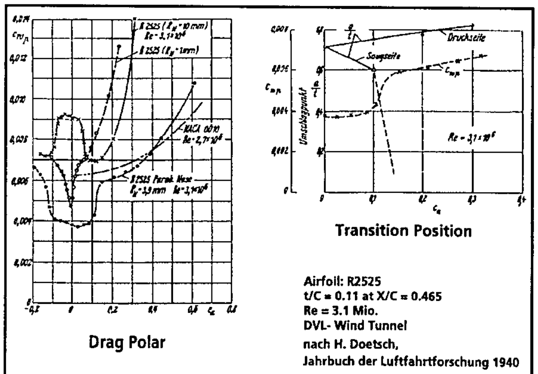
Sphere Test without and with Tripping Wire

Figure 1

experiments demonstrated that the boundary layer and its behaviour could be influenced from outside. One of the major questions to answer in the following years was, what are the reasons that lead to that different behaviour of the boundary layer. Very early Osborne Reynolds postulated, that the transition from laminar to turbulent flow could be a stability problem. The research activities initiated by Prandtl in 1921 in the following years led to the stability theory of laminar boundary layers in 1929.

In the following roughly three decades from 1930 to 1960 laminar flow research made ist first steps to application mostly on sailplanes or gliders, may be it could be entitled as moving from fluid dynamics research to aerodynamic research. The development might be described by three examples that have the characters of milestones.

The first tests on laminar airfoils were carried out in 1938. One example is taken out of the „Jahrbuch der deutschen Luftfahrtforschung 1940), where drag polars of several airfoils were collected (Figure 2). The results clearly show the potential of drag reduction. Several experiments with different nose shapes also made clear, that the shaping of airfoils is essential and has to be done carefully to gain the benefits.

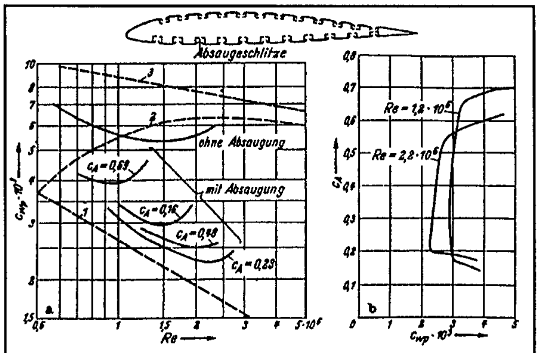


First Tests on Laminar Airfoils (1938)

Figure 2

Still not answered was the question, is it possible or are there criteria to predict the transition from laminar to turbulent flow? First steps in using the stability theory for the prediction of transition were published by Schlichting /Ulrich 1942. They presented a first transition criterion based on stability considerations of laminar boundary layers. It was obvious that the correct prediction of transition was – and still is today – one of the major challenges in laminar flow research.

Another milestone where the experiments of Pfenninger in Zurich 1946, were he demonstrated, that not only shaping of the airfoil but also the damping of the disturbances in a laminar boundary layer by boundary layer suction through a slotted surface with a suction device integrated in an airfoil leads to promising results (Figure 3). The Figure 3 shows the drag coefficient as function of the Reynolds-number and compares one case



First Tests on Laminar Airfoils with Suction (1946)

Figure 3

without suction with different cases with suction, with considerably lower drag-coefficient.

After World War II aerodynamic research in Germany was stopped for several years.

The renaissance of laminar flow research started in DLR (former DVFLR) with a significant effort around 1980. Before that time only laminar airfoils for sailplanes had been investigated.

Laminar Flow Research in DLR

After World War II there was a dramatic change in aircraft design in the following 25 years. The major improvements were the introduction of jet-engines and swept wings combined with higher cruising speeds. As laminar flow wing technology before 1980 was mainly used in sailplane or glider design the rapid increase in fuel price in the seventies directed the research objectives to laminar flow also for larger commercial aircraft.

A national German research programme "Laminar Flow Wing" was initiated by industry, universities and DLR, funded mainly by the German government. The clear objective was the development of design knowledge for laminar flow application on civil transport aircraft.

Two options for laminar flow wing technology can be distinguished (Figure 4):

1. Natural Laminar Flow (NLF)

Used on aircraft with unswept wings as gliders, small aircraft, Regioliners with turboprop engines, transport aircraft and swept wing

Laminar Flow Wing Technology

Natural Laminar Flow
Control of Tollmien-Schlichting-Instability by Pressure Gradient (Shaping)

- Unswept Wings
  Gliders, General Aviation Aircraft, Small Regioliner, Transport Aircraft
- Swept Wings
  Regioliner, Transport Aircraft with Moderate Sweep (20); Moderate Re-Numbers

Hybrid Laminar Flow
Control of Crossflow-Instability in the Leading Edge Region +
Control of Tollmien-Schlichting-Instability by Pressure Gradient

- Swept Wings
  Transport Aircraft Wings with High Sweep (>20) and High Re-Numbers

Figure 4

aircraft with moderate sweep and moderate Reynolds numbers for Regioliners.

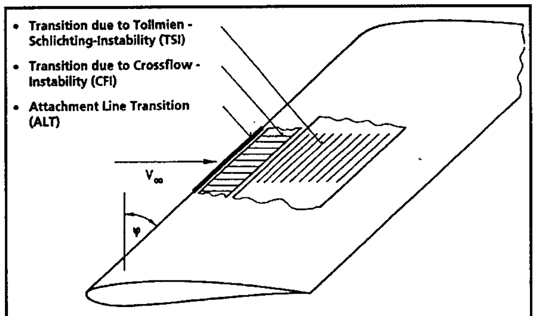
2. **Hybrid Laminar Flow (HLF)**

Used for swept wings with higher sweep and high Reynolds numbers as modern civil transport aircraft have.

The major reason for this splitting is, that different mechanisms of boundary layer instability have to be taken into account. For unswept wings the laminar boundary layer becomes unstable due to Tollmien-Schlichting-waves which can be damped or controlled by the pressure gradient of the wing section – natural laminar flow.

For swept wings in the leading edge region crossflow instabilities dominate the boundary layer, which for moderate Reynolds numbers and moderate sweep angles can be controlled by carefully shaping the wing nose.

For wings with higher sweep angles and higher Reynolds numbers crossflow instabilities in the leading edge region can only be controlled and damped by boundary layer suction in the wing nose region followed by natural laminar flow further downstream – hybrid laminar flow (Figure 5).



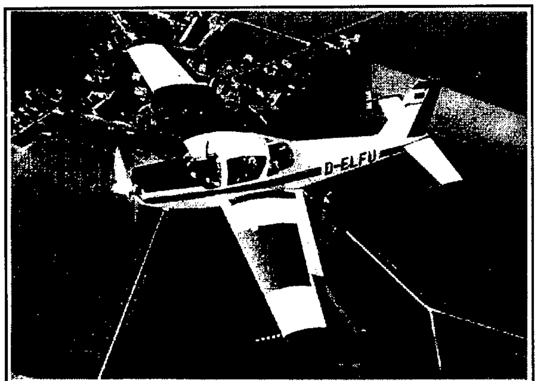
Transition Mechanisms on Swept Wings

Figure 5

The crucial point in the design of laminar flow wings for higher Reynolds numbers is a reliable engineering design tool for transition prediction. There were in 1980 – and are still today – no purely theoretical methods available for transition prediction. Purely empirical correlation based on wind tunnel experiments on 2d-airfoils could not be used for swept wing designs and high Reynolds numbers.

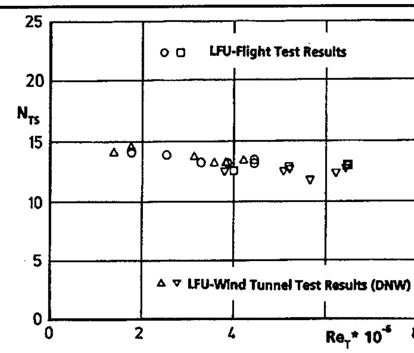
Therefore DLR decided to use the so-called N-Factor method for transition prediction based on linear stability theory of laminar boundary layers. This method has to be calibrated for Tollmien-Schlichting- and crossflow-instabilities by carefully executed flight and wind tunnel experiments to determine so-called limiting N-Factors for transition. It should be noted here, that today this N-factor method is also used for numerical calculations in Navier-Stokes simulations.

The first step in the research strategy of DLR was the establishment of a reliable transition prediction procedure based on the linear stability theory by calibrating the N-Factor method and determining limiting N-Factors in flight and wind tunnel tests.



Flight Tests with LFU-205 with Laminar Glove

Figure 6

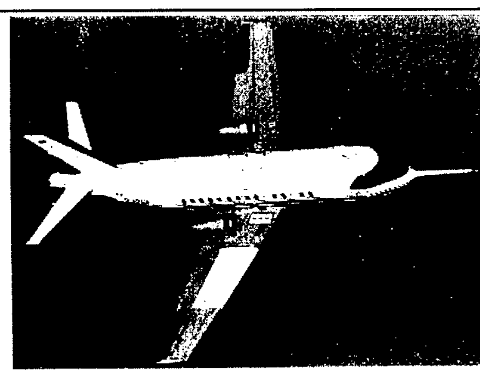


Calculated N-Factors of TS - Waves at Transition

Figure 7

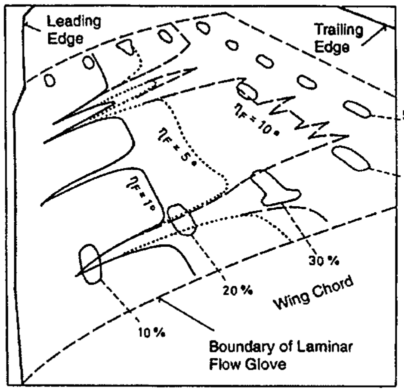
For unswept wings the small DLR research aircraft LFU-205 was used in flight and wind tunnel tests. Figure 6 shows the aircraft equipped with a laminar glove on the right wing (in red). The results of these tests in flight and in the large low speed wind tunnel of DNW were used to determine limiting N-Factors due to Tollmien-Schlichting instability at the transition location (Figure 7).

For swept wings the calibration of the N-Factor method for Tollmien-Schlichting- and crossflow-instabilities was done with the DLR research aircraft VFW 614/ATTAS in co-operation with industry. Figure 8 shows the aircraft equipped with a laminar glove on the right wing during flight testing. Figure 9 presents one of the



Flight Tests with ATTAS/VFW 614 with Laminar Glove

Figure 8

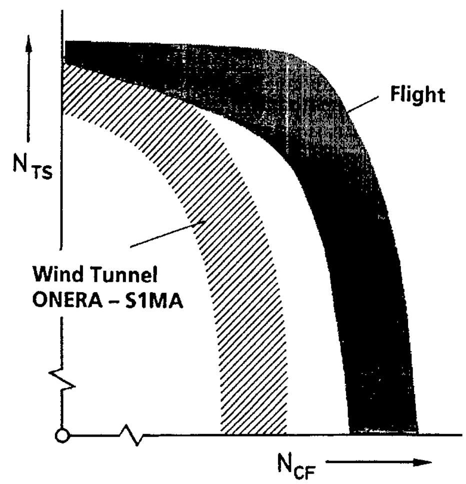


Changes of Transition Location by Increasing Flap Angles Observed in Flight by Infrared image Technique on ATTAS/VFW 614 Glove (M = 0,34, Re = 20×10⁶)

Figure 9

results of transition lines on the glove depicted from infrared images obtained in flight. The limiting N-Factors due to Tollmien-Schlichting- and due to crossflow-instabilities are shown in Figure 10 for flight tests and for wind tunnel tests obtained in the ONERA-S1MA wind tunnel. Due to different disturbance levels in free atmosphere and in wind tunnel the limiting N-Factors are different.

The curves of Figures 7 and 10 will be used as limiting N-Factors in an engineering transition prediction procedure.

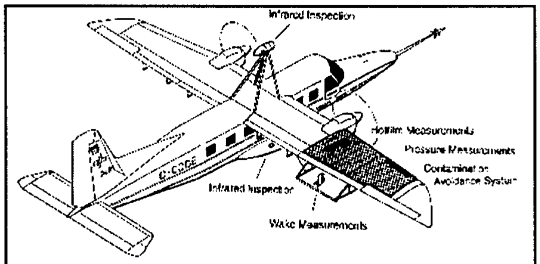


Limiting N-Factors for Transition Prediction in Flight and in S1MA Wind Tunnel for Swept Wings

Figure 10

The N-Factor method calibrated in flight and in wind tunnel was in the second step of the DLR research strategy successfully applied in designing laminar flow wing gloves for real aircraft application.

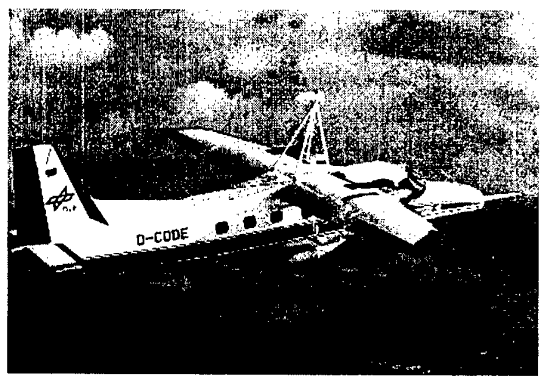
In co-operation with Dornier Luftfahrt a laminar flow wing glove for the Dornier DO 228 aircraft – a research aircraft of DLR – was designed and flight tested. Figure 11 gives an impression of the test equipment, showing infrared inspection of upper and lower glove surface, hotfilm measurement in the boundary layer, wake rake measurements as



Do 228 Aircraft with Laminar Glove and Measurement Equipment

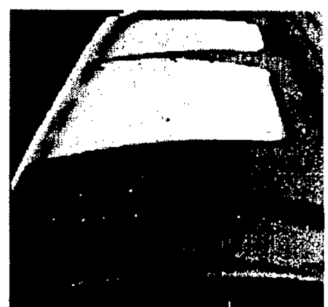
Figure 11

well as pressure distribution measurements on the glove. Figure 12 shows the aircraft with the test equipment during flight. Figure 13 gives one example of an infrared image of the upper surface, indicating laminar boundary layers on the upper glove surface up to 55% of wing chord.



Test Aircraft Do228 with Laminar Glove

Figure 12



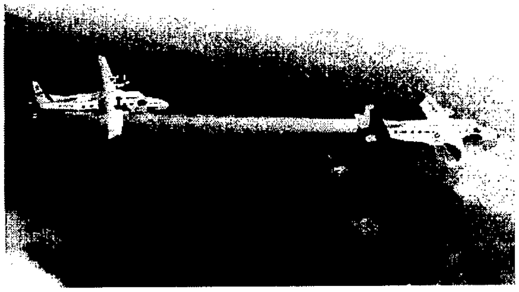
violet = turbulent / yellow = laminar

Infrared Image on Laminar Glove of Do228 with Transition

Figure 13

Operational aspects of laminar flow as contamination and icing problems have also been investigated and have been successfully solved in that project. Figure 14 gives an impression of de-icing flight tests with a water spay aircraft flying in front of the test aircraft. All tests showed that laminar flow wing technology for unswept wings is mature to be incorporated in new aircraft design.

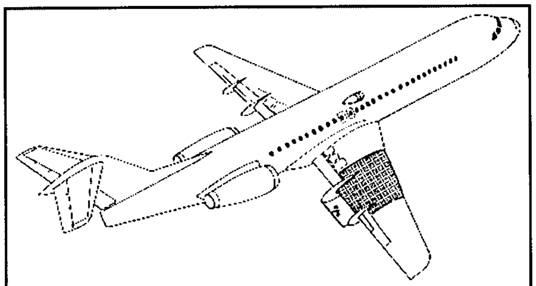
The application of laminar flow wing technology for natural laminar flow on swept wings was successfully done in an European co-operation ELFIN I (European Laminar Flow Investigations)



Formation Flight of Test Aircraft and Water Spray Aircraft for De-Icing Investigations

Figure 14

on a Fokker F100 aircraft also equipped with a laminar flow glove (Figure 15). This programme also validated the DLR design philosophy of laminar wing design based on the N-Factor method. Figure 16 shows the laminar glove on the Fokker F100 in flight.



Fokker F100 Aircraft With Laminar Glove used in ELFIN I Flight Tests

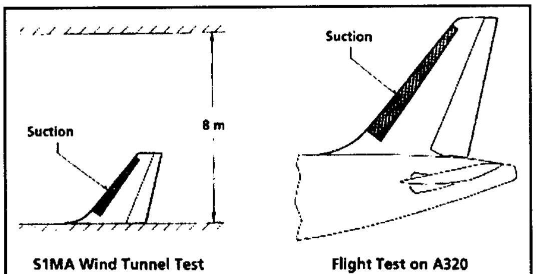
Figure 15

Fokker F100 Aircraft for Laminar Flow Wing Flight Testing BRITE/EURAM (ELFIN I) of EU

Figure 16

The success of ELFIN I was the basis for several follow-on projects now focussing on the next step in developing the laminar flow technology for highly swept wings – the hybrid laminar flow. Elfin II, HYLDA and HYLTEC again were projects financed by the European Union. Main partners have been Airbus partner companies, DLR and ONERA.

The objective was to design and verify a laminar flow wing with leading edge suction. Furthermore Airbus Industries, Airbus partner companies, DLR and ONERA executed a joint programme verifying the hybrid laminar flow technology on an Airbus A320 fin in flight. Prior to the flight tests the fin was tested with a ½-scale model of the fin in the ONERA-S1MA wind tunnel (Figures 17 and 18) with a 8m diameter test section. Promising results of these tests convinced industry to launch a flight test programme, which was successfully carried out in 1998 on an A320 aircraft. Figure 19 shows the suction fin on the test aircraft. Hybrid laminar flow technology was successfully demonstrated in flight and the engineering design tool for transition prediction with the N-Factor method was proven as feasible. A significant reduction in drag was realised. Figure 20 gives one example out of the test series showing the laminar flow regions on the fin.

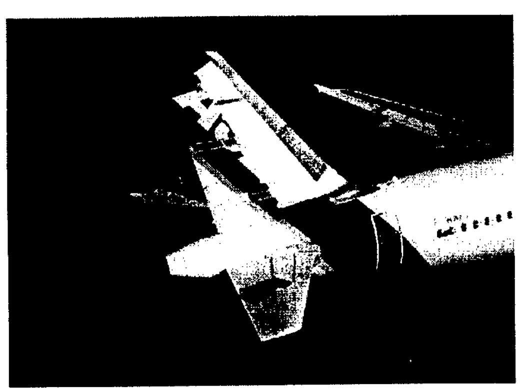


Technology of Hybrid Laminar Flow Control on Airbus A320 FIN

Figure 17

A320 Fin Model in ONERA S1Ma

Figure 18



A320 Fin with Boundary-Layer Suction in Flight Test

Figure 19

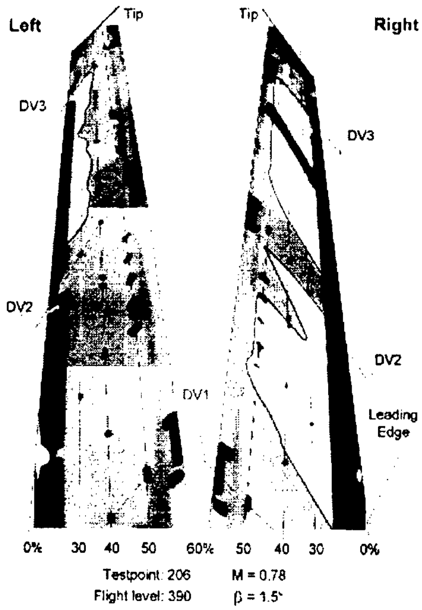


Figure 13

Summary

The HYLTEC project was the last highlight in a long history of continuous and successful development of laminar flow technology consequently carried out step by step. A new project ALTTA financed by the European Union has already started this year. But this is – hopefully – not the end of the story. There are still problems to be solved.

I am sure that some researchers disagree with my following conclusions: In a long series of tests laminar flow technology has been proven. It is very near to application. Taking into account the demonstrated potential of that technology it is now mainly up to the industry – together with research – to take over the responsibility for the further development of laminar flow technology and make it mature for application. Then we will see in the near future – more than hundred years after Prandtl formulated the basic scientific theory- transport aircrafts flying with laminar technology.

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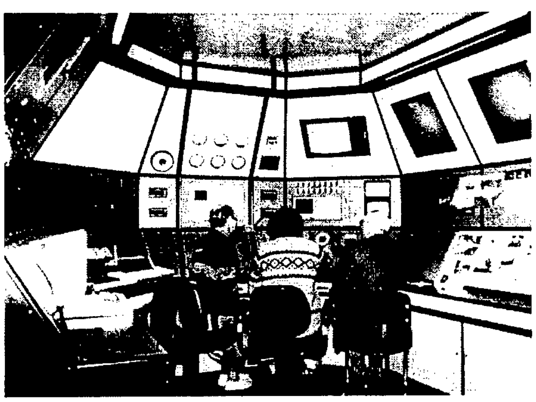
Johns Hopkins Univ. Assit. Prof. 1964-1965
Univ. of Pittsburgh Assoc. Prof. 1965-1968
Technion
Israel Inst. Tech. - TIIT Assoc. Prof. 1968-1972
Prof. since 1972
Sabbatical Leave, USA, 1974-1975
Sabbatical Leave, EU/USA, 1999-2001
1984 Editor-in-Chief, *Int'l J. Turbo & Jet-Engines*
1973-1999 Founder and Head, *Gas Turbine & Jet-Engine Laboratory*, Technion-IIT;
1976-1978 1st Director of the *Neaman Inst. for Advanced Science and Tech.* ['under development'], including chairing of two *National-Policy Workshops on links between Industry, Government and Academia*
Co-Chrm: Fluid Dyn. Levich Conf.
Oxford Univ., UK, 1977
U.S. Nat. Acad. Sci., Washington DC, 1978
Chairman: *ASME International Conf. on Turbo and Jet Engines*, Haifa, TIIT, 1979;
AIAA Aircraft Comt. [Member 1990 – 1993];
AIAA Air-Breathing Engines Comt. [Member 1975-77];
AWARD: *N.Y. Academy of Sciences Gold-Medal-Award* for *The Crisis Over the Origin Of Irreversibility, Science, 176, 11-17, 1972* [The Early Foundations of GRAVITISM]

THE NEW ERA OF FLIGHT CONTROL & SAFETY

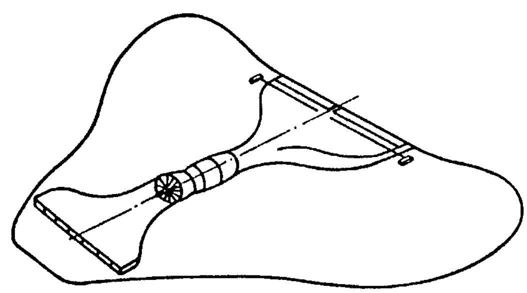
At the end of the first 100 years of conventional, highly dangerous, Aerodynamic Flight Control [AFC] based civil and military jet transports, we enter a new era of flight control. It is marked by COMPLETE (roll-yaw-pitch) Thrust Vectoring Flight Control [TVFC] and maximization of agility and flight safety (1-55).



Complete TVFC is stall-spin free and much more effective than AFC in both pre and post-stall flight domains, in take-off and in landing. The leading TVFC fighters today belong to the SU-30-MK family. An example from our Standard Agility and Safety Comparison Maneuvers (SASCOM) for sub-scale and full-scale flight-testing conditions for emulations and simulations is presented for the SU-30MKI and its engine.

By deflecting engine-nozzle(s) as fast as current AFC surfaces, TVFC prevents most air catastrophes, saves many lives and prevents much damage in both military and civil domains.

Since 1987 the author has demonstrated, by flying sub-scales and for the first time in aviation history, complete TVFC with tailless-stealthy designs.

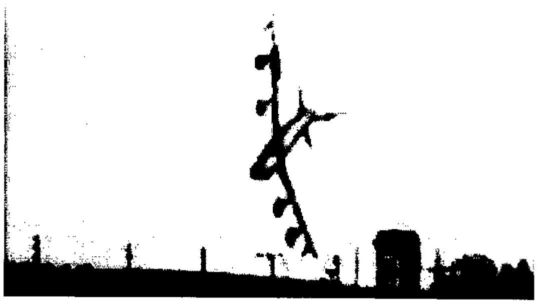


Since 1995 these flights include vectored F-22 and vectored jet transport sub-scales with reduced tails.

This paper stresses the need for dynamic, sub-scaling flight testing, between wind-tunnel tests and full-scale ones. It also re-assess air transport policy, aero education and research, while maintaining that all civil transport jets are to be vectored, sooner or later, by legislation and certification regulations.

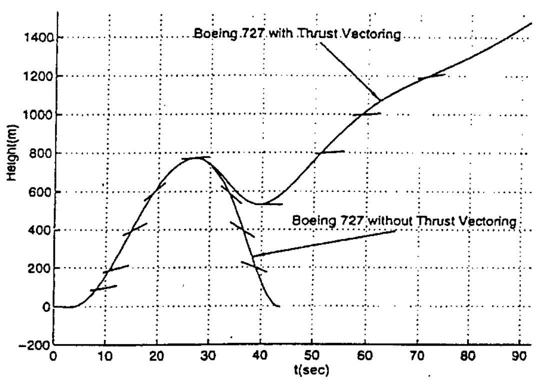
Introduction

Most air catastrophes are caused by the limited capability of Conventional Flight Control [CFC] or AFC, for Aerodynamic-only based CFC, to prevent them or to actively save doomed passenger, business and cargo jet transports during take-off, flight and landing under adverse conditions involving stall/spin, asymmetric icing, wind-shear – microbursts, partial loss of AFC and engines, total loss of all hydraulics, tire explosions and front-wheel collapse. Similar catastrophes are encountered by turbo-prop aircraft. Other catastrophes involve the loss of tail rotor or tail during helicopter flight [1-55].



What Is Thrust-Vectoring-Effected Recovery ?

An example of **post take-off** crash is discussed and depicted on the right. The altitude is marked by meters and the time by seconds. About 28 seconds post wheels-up, at an altitude of about 800 meters, AFC is suddenly lost. It is immaterial now why AFC was lost. We shall discuss that later. The key issue is that without TVFC, and within about 25 seconds, the aircraft is bound to crash into the ground.



The thrust-vectoring effected recovery is depicted in comparison for the case of a Boeing 727 whose AFC is unable to prevent such a catastrophe. The methodology, methods and specifics of the TVFC used can vary. A few examples are discussed below. Yet, the next key issue is to save the aircraft from crashing within about 25 seconds. It takes about 15 seconds for the normally-retracted TVFC system to be deployed and become operational. The pilot can now safely stabilize the aircraft and recover from the impeding catastrophe. He can then land safely or proceed to increase altitude.

Thrust Vectoring Maximizes Close Combat Agility

Maximized agility proof-of-concept flight tests in the deep post-stall domain were first conducted in Israel in 1987 using tailless, stealthy, subscaled cold-jet powered vehicles.

Maximized agility proof-of-concept flight tests in the deep post-stall domain using full-scaled aircraft (the depicted U.S.-German experimental X-31) were conducted in the USA in 1994. A nominal 32 to 1 kill ratio advantage of vectored over conventional fighter has thus been well re-demonstrated with actual aircraft (Table below). Since then the very strong opposition to add TVFC kits to military fighters, or to re-design them as vectored-stealthy vehicles (Annex I) has subsided, but only in the military domain (see below).

KILL RATIOS BY A VECTORED FIGHTER OVER CONVENTIONAL ADVERSARIES

Kill Results In Favor of :	Vectored X-31	Conv. F-18	Neutral	Kill Ratio Advantage
X-31 Offensive	4	0	0	>> 32
Line Abreast	63	2	4	31.5
X-31 Defensive	10	6	4	1.6
X-31 is not activating its thrust-vectoring post-nozzle paddles				minus 2.4

Minimal Avionics Change for Pure or Mixed AFC-TVFC

Conventional aviation is pure AFC-based. Completely thrust vectored controlled vehicles belong to pure future vectored aviation (Cf. the X-44). Anything in between we term mixed AFC-TVFC. No or little change in avionics is required for both pure TVFC and for mixed AFC-TVFC. FMC (Flight Management Compute) is to be only slightly upgraded with various pure or mixed AFC-TVFC options, and the jet transport pilot is to select a mode of control in case of emergency.

Advances in the air safety domain do not depend on conventional aerodynamic stability criteria, research, re-optimisation, re-design, etc. This becomes clearer when one faces emergency "SASCOM" needs (see below), in which the first redundant variables to be deleted, are the aerodynamic ones.

The First-Ever Completely Vectored Flight Tests

Complete (Yaw-Roll-Pitch) thrust-vectoring jet-engine nozzles and tailless, stealthy vehicles were designed, wind-tunnel tested, jet-lab-tested, constructed, instrumented and flight tested in Israel in 1987 by the author?s team, using radio-controlled sub-scales.

These first flights were the outcome of the development by the author of various Yaw-Roll-Pitch (YRP) TVFC jet-engine nozzles since 1980. That research has also produced a family of retractable and non-retractable YRP TVFC nozzles and TVFC methods and systems, with and without thrust-reversing [TR] for jet transports and turbo-props. The focus of these efforts has been maximization of air

safety in operating transport jets, turbo-props, helicopters and ground & sea vehicles. The resulting integrated methods and systems are aimed to minimize installation complexity, weight and cost, while allowing, under adverse conditions, the highest transport safety levels feasible.

The New Thrust Vectoring/Reversing Systems for Air Transports

Various thrust-reversing (TR) designs exist. TR is in fact a mode of thrust vectoring. Yet, it is a very sluggish, un-effective and a dangerous mode, if used in flight. The key safety issue is, therefore, to add emergency-only TVFC-system without eliminating the TR mode for landing, but with minimal weight-cost addition – or none at all. This has already been done (11-13, 23)

This research has been conducted at the jet laboratory shown. In the air transport domain (military and civil) it is to provide pure TVFC when AFC fails, or fails to function safely.

In their deployed, emergency-only TVFC modes, our designs are not optimised for normal flight, for their sole purpose is to prevent a catastrophe, and/or to land the aircraft safely in the nearest airport. In their retracted mode the new designs do not at all interfere with engine/nacelle/airframe aerodynamics. The retracted modes are, therefore, inoperative during normal take-off, landing and cruise flight (23)

In previous studies we have proved that transport TVFC can prevent at least 60% of the accidents. The predictions are that it can save most doomed aircraft whose AFC elements have failed, or whose all airframe hydraulics/actuators are not functioning, or one or more of the engines is inoperative, or has separated, or the transport jet, or turbo-prop, is subjected to adverse flying conditions, such as stall/spin, asymmetric icing, and wind-shear/microbursts.

Our previous simulations also show that transport TVFC provides the pilot with a new very powerful capability: He can reliably and rapidly correct final accident-causing attitudes, or his own mistakes, generated under the most critical situations involving adverse takeoff, flight and landing conditions. The technical issue remains to minimize the deployment time under such conditions. This remains an open issue for flight-control simulations and implementations.

Weight-Cost Issues of Add-On Kits

TVFC/TR system configurations for jet transports should not be heavy, complex and costly in comparison with extant conventional TR doors/rods/hinges, retracting/sliding gears, actuators and TR-grid-nacelle-structures. In fact they can be less in each or most of these categories. Some TR designs can be easily removed and cost-effectively replaced with a simpler and lighter-weight add-on TVFC/TR kits (11-13, 23). TVFC/TR-systems allow shorter landing distances via reduced minimum control approach speed, to be followed by the conventional, unchanged, post-touch-down TR.

TVFC/TR-system designs are to be implemented in two regions: The cold fan-air and the hot core jet. Unlike the fighter engines we deal here with fixed area jet-engine nozzles.

In conclusion, TVFC/TR-system designs are to be implemented without any change to the engine nozzles and the engine itself, while providing low-cost, low-weight, retractable/integrated add-on kits for upgrading extant civil and military jet transports

World's First Tailless Vectored Vehicle Proof-of-Concept

The first TVFC-engine-nozzles and TVFC-sub-scaled airframes were flight tested by the author in 1987 [5].

That included the first Tailless Vectored Vehicles [TVVs] as defined and characterized by the author's book. It was conducted by flying TVFC-Unmanned Aerial Vehicles [UAVs]. New TVFC-induced post-stall manoeuvres, including positive and negative cobra manoeuvres up to 170 deg. angle of attack and turning at up to 50 deg. sideslip angles, have thus been substantiated for the first time.

These flight tests have demonstrated the highest payoffs at the weakest domains of AFC, i.e., at low (or zero) speeds, conventionally-uncontrolled spins, very-short runways, and during rapid post-stall manoeuvres. TVFC has been employed mainly when ailerons, elevators and rudders have been neutralized in flight.

In 95 the author has also conducted the first flight tests with a sub-scaled TVFC Boeing 727 prototype to provided the first proof of maximized-safety, thrust-vectoring-based, alternative transport flight control for saving otherwise doomed jets [4]. If TVFC kits are mounted as mixed TVFC-AFC ones, the resulting technologies are estimated to potentially prevent more than 50% of jet crashes as caused by:

- stall-spin,
- AFC-failures, or failures to function,
- icing,
- windshear,
- micro-bursts and
- takeoff & landing during strong cross winds, low speed and loss of all airframe hydraulics

To conclude: YRP jet-deflecting engine nozzles for civil and military air transport are to open the road to safer flight control. Yet, the situation in civilizing the more verified military thrust-vectoring technologies for maximizing air travel safety may be suffering today from a cultural scepticism somewhat more intense than that encountered earlier in the military domain prior to the X-31 flight tests.

New Flight Safety Standards

Our estimations of expected public benefits from civil TVFC technology are based on U.S.

NTSB's detailed reports on causes of transport jets fatal accidents during the last 30 years. Using these reports we have examined under what realistic TVFC means and commands such crashes might have been prevented [4]. Our conclusions show that mixed TVFC-AFC can prevent most air fatalities when the jets encounter:

1 – total airframe hydraulic systems failures;
2 – severe mechanical failures, or separations, of AFC surfaces;
3 – severe stall/spin uncontrollability;
4 – windshear-induced uncontrollability;
5 – icy-runway-induced uncontrollability ;
6 – icy-rain-induced uncontrollability ;
7 – tire-blow-induced uncontrollability ;
8 – last-minute, beyond AFC capability landing corrections;
9 – asymmetric loss of propulsion;
10– loss of AFC capability in the deep post-stall/ low-or-zero-speed domain.

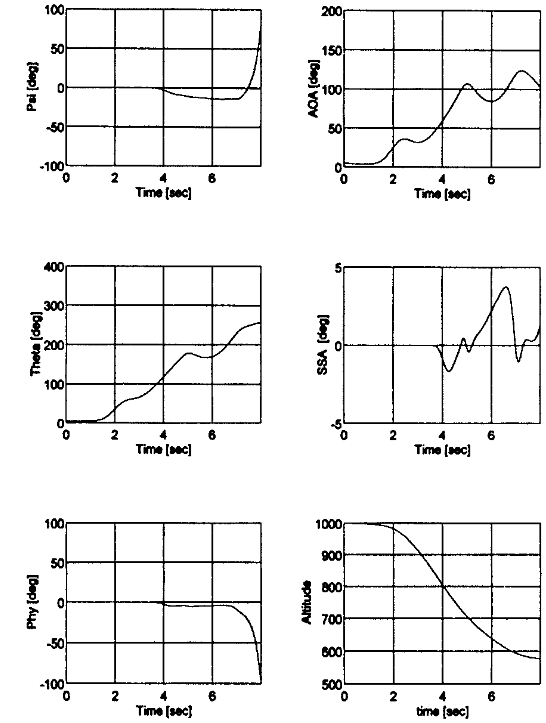
The resulting flight safety levels are expected to be even higher for the following reason: Most NTSB's reported "Pilot Error" cases have not been counted by us for our flight simulations show that, with TVFC, the pilots had time-options to recover from what is termed "his mistakes". A simple example: Crash avoidance into a mountain in cases requiring post-stall manoeuvres, which had been filed by NTSB as "Pilot Error". Our studies also indicate reduced runway needs.

It thus remains for near-term international education, legislation and certification to help save many lives and prevent much damage by thrust vectoring.

Reassessing Aero-Education

Jet engines are traditionally treated in class as providing only brute, unvectorable force. The required moments for manoeuvrability, controllability and air safety are traditionally reserved only for aerodynamic-based flight control [AFC] surfaces, which are, a-priori, limited by external-flow regimes, and, hence, are limited by the so-called stall barrier and spin dangers. Re-educate the aero-professors is easier said than done. It would take a new generation of faculty to fundamentally change aero-education in academic class and in pilot training.

In the industry and aero-research entities the old design approaches should be re-assessed, now. One can learn from the combat pilot re-training, where a fundamental change in such low-insight attitudes, has already caused dramatic changes in maximizing agility, stealth and post-stall controllability and safety. Indeed, new attempts to revolutionize the mode of thinking of propulsion, aerodynamic, system design and flight-control engineers, dictate a radical change in basic aeronautical engineering and pilot education, theories and aircraft design practice.

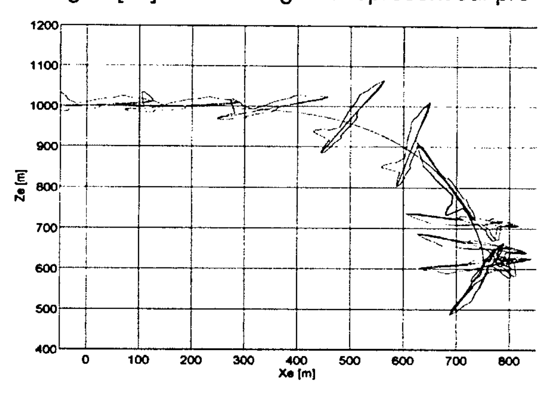


Tailless Vectored Aircraft

Since 1987 we have also stressed and demonstrated various tailless fighter aircraft and tailless transport models and computer simulations. Each such design may represent the same safety level as that provided by category 4. This category-design was first flight tested by us in 1987 [2, 5].

Flight Safety Effectiveness

Flight safety also depends on the distance between engine nozzles [not necessarily between engines] and aircraft center of mass location, and on maximum feasible jet deflections and deflection rate values. Maximization of flight safety also requires automatic, or manual emergency transformation means from TVFC mode to AFC, and vice versa, including emergency release/neutralization means to zero TVFC, or zero AFC moments. It also requires 'CONTROL ALLOCATION', a key concept that we study with new Minimum Time Standard Agility and Safety Comparison Manoeuvres [SASCOM] and flight testing methodologies [14]. The next figures represent our pro-



posed Flight Testing Standards for TVFC to maximize kill ratios, post-stall agility and flight safety.

The "Voll" Maneuver

Roll around the velocity vector is termed in these standards "voll". Voll becomes a pure yaw rotation ("helicopter manoeuvre") at 90 degrees angle of attack (AOA). Many new post-stall Maneuvers are currently under study in various laboratories and flight-testing sites around the globe. What is stressed below is the minimization of response times to unit operational (UO) commands involving voll, yaw and pitch at high AOA values (14, 37).

A SASCOM Simulation with SU 30 MK ("SU-37")

An example from our SASCOM pitch simulations of such a nominal fighter is presented below. These include our SASCOM-thrust simulations of the "Installed" Lyulka (Saturn) AL-31FM engine.

The UO commands in this case (not depicted) are the SASCOM standard TV set plus commands to the canards, but none to the elevators. This example is based on our various estimations methods and on the SASCOM set of mathematical equations (9, 16, 17, 18, 21, 37).

Tailless Vectored Transport Aircraft

Since 1987 we have also stressed and demonstrated various tailless fighter aircraft and tailless transport designs. Each such transport design represents the same safety level as that provided by our fighter aircraft designs. And these have been well-emulated by us with proper dynamic similarity rules and flight testing with cold-jet-propulsion systems and radio-controlled subscales since 1987 [2, 5].

Effectiveness

Flight safety also depends on the distance between engine nozzles [not necessarily between engines] and aircraft center of mass location, and on maximum feasible jet deflections and deflection rate values. Maximization of flight safety also requires automatic, or manual emergency transformation means from TVFC mode to AFC, and vice versa, including emergency release/neutralization means to zero TVFC, or zero AFC moments. It also requires 'CONTROL ALLOCATION', a key concept that we study with new Minimum Time Standard Agility and Safety Comparison Manoeuvres [SASCOM] and flight testing methodologies [14]. The next figures represent our proposed Flight Testing Standards for TVFC to maximize kill ratios, post-stall agility and flight safety.

The "Voll" Maneuver

Roll around the velocity vector is termed in these standards "voll". Voll becomes a pure yaw rotation ("helicopter manoeuvre") at 90 degrees angle of attack (AOA). Many new post-stall Maneuvers are currently under study in various laboratories and flight-testing sites around the globe. What is stressed below is the minimization of response times to unit operational (UO) commands involving voll, yaw and pitch at high AOA values (14, 37).

A SASCOM Simulation with Russian Vectored SU-30MK ("SU-37")

An example from our SASCOM pitch simulations of such a nominal fighter is presented above. It includes our SASCOM-thrust simulations of the "Installed" Lyulka (Saturn) AL-31FM engine of the Russian SU-35 ("37" or "MKI").

The commands in this case (not depicted) are the SASCOM standard TV set plus commands to the canards, but none to the elevators. This example is based on our various estimation methods and on the SASCOM set of mathematical formulations (9, 16, 17, 18, 21, 37).

References

Flight-testing, laboratory tests, mathematical similarity formulations and simulations mentioned are detailed in 55 publications listed below, a few dozen internal-classified seminars and 29 reports and Reviews for funded TVFC Projects conducted by the author during 1980-2000: USAF, GE, PWA, LM (GD), Boeing (MDD, C-17 Transport), Teledyne, DOT-FAA, and with no funding, with entities in the EU, China, Poland, India, South Africa and Taiwan.

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At present he is engaged in a seach project on the development of a flight control system for an autonomous flighting robot.

MODELLING, SIMULATION AND IDENTIFICATION OF THE AUTONOMOUS FLYING ROBOT WITH MATLAB/SIMULINK

This lecture was developed in the frame of the project "Flight control for spherical air-ships" at the "Hochschule Bremen" under the initiative of Prof. Dr. Apel and with the kind support of Prof. Dr. Buchholz.

Table of Contents:

1. Introduction

The use of autonomous flying-robots can reach important commercial significance these days. It promises great advantages over other methods in Cartography, in profile-photography, in the search of fossil sites or in the monitoring of air pollution.

All these applications require high demands on positioning the air-ship and on its preprogrammed routing.

The results presented below were obtained within the program-environment MATLAB/ SIMULNK® in its Version 5.3.

2. Modeling the Dynamical Behavior using MATLAB/Simulink®

The expensive development of modern systems, specifically in the air- and space-technology, is closely related with its mathematical modeling. With a theoretical analysis we can describe the behavior of the model in response to the external disturbances in terms of forces and momenta.

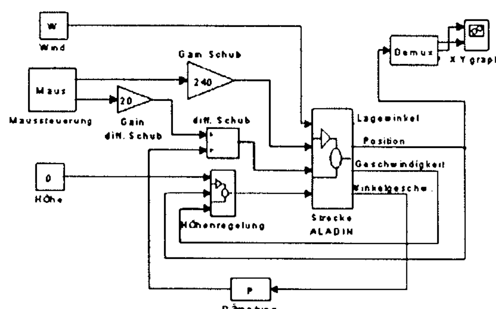
Within the frame of the theoretical analysis one should undertake the following steps:

1. Structure definition:
a) qualitative description of the object and its environment
b) fixing the model's structure

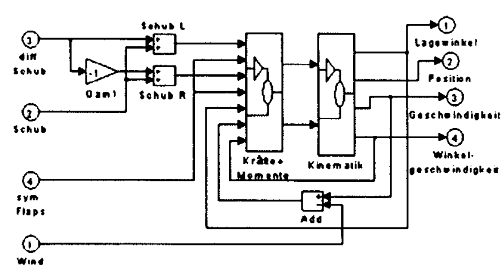
With this we obtain the elements of the controlled system, where the order of elements gets fixed by the model's equations. As first intermediate result one obtains a qualitative model.

2. Recognition of parameters:
a) formulation of equations for a qualitative model
b) determination (from the calculations and earlier experiences) of the model parameters (mass, momenta, forces...)

As second intermediate resultone obtains a quantitative result. The modeling of the aerodynamic behavior can be exemplified by a spherical autonome airship, for which the following model was developed:



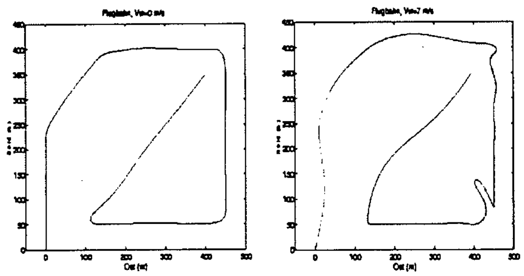
The scheme contains in total 21 subsystems and has several layers. The subsystem "Path" has the following appearance:



This scheme was buitt up out of existent Si mulink-b locks, due to the known classical flight-mechanic equations.

The flight path can be preprogrammed as a m-file, saved in the model and run during the simulation.

With a given south-west wind (of about 7 m/s) the model responds correspondingly to its parameters and control properties:



3. Simulation of the Theoretical Model

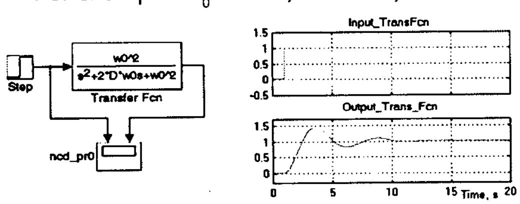
We do this as usual:

- all exterior influences are excluded. Thus we gain statical stability for the model.
- the forces are included one after the other in order to find dynamical instabilities when the model is taken slightly out of its statical equilibrium.

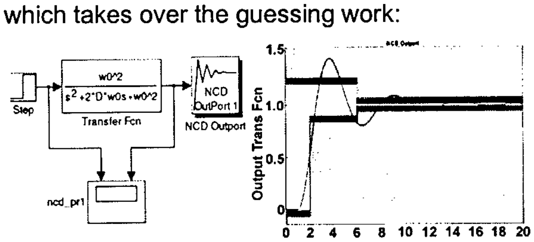
It is meaningful to took into the specialized literature [9,10,11,12] in order to find out how to build and analize various models using MATLAB/ Simulink®. Here we want to show one simple example, tor the powerful ncd-btockset [13] tool.

Lets take an element PT_2 to be analyzed. Until now it looked as follows: one builds a model in a model-window, gives various signals, obtaines correspondingly various responses and tries to achieve the wanted transfer function. In the past, the parameters were entered based on experience or sometimes by shear guessing:

For example: $w_0 = 1.25$; $D = 0.25$;



In contrast, when one uses the relatively new NCD-Outport-block, within an NCD-Blockset, which takes over the guessing work:



After a double-dick on the block NCD-OutPort icon, the figure above appears. Per default, upper and lower bounds for the graphs range are taken by the program. We can reset these bounds manually with drag-and-drop, in the order to get the desired output range for the curve. This window is named: System:<filename>, Outport:<PortNr.> and has the following menue-list:

File	Edit	Options	Optimization	Style
Load...	Undo Ctrl+Z	Initial response Ctrl+I	Start Ctrl+T	Grid
Close Ctrl+W	Edit constraint... Ctrl+0	Referece input-	Stop	Snap
Save Ctrl+S	Delete plots Ctrl+X	Step response...	Parameters...	Hot-Key help...
Print Ctrl+P		Time range...	Uncertainty...	Readme.m...
		Y-Axis...		
		Refresh		

Here we just want to take a view on some special menue points:

Edit constraints: after clicking on the bound to mark it, it permits to enter the above mentioned range for the graphs manually, as coordinates instead of drag and drop.

Initial response: First, the output signal appears without the optimization procedure. The default values for "Reference input" and "Step response" can be left in this first step.

Time range: As a rule, the time range and the start- and stop-times are coordinated automatically by the model-window.

The researcher has the possibility to set manually his own description for the axes.

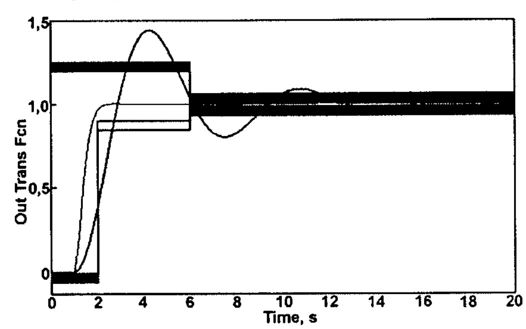
Refresh: restores the bounds to their default position.

The most important points are hidden under the menue-option „Optimization":

Start: Here we start what the ncd-outport is really meant for: the optimization.

For this purpose, we have to enter the tunable parameters in the Parameters... window, one after the other, separated by spaces.

In our case are they w0 and D. Then the following happens:



The oscillating (in black) start curve transforms itself into a new (soft-green) one, that fits very well into the prescribed boundaries. The command window prompts that the optimization converged successfully and by giving in there ">>w0" it outputs:

$w_0 = 4.2921$ and after the input: ">>D" it returns: $D = 0.9035$, as new optimized values for w_0 and D.

As the experience shows us, the optimization runs well even in deep level systems with many variables.

4. System Identification

After a mathematical model is designed and simulated, after having constructed a physical model and

tested it experimentally, we still have a central problem: how to identify and optimize the parameters for both (specially non-measurable parameters).

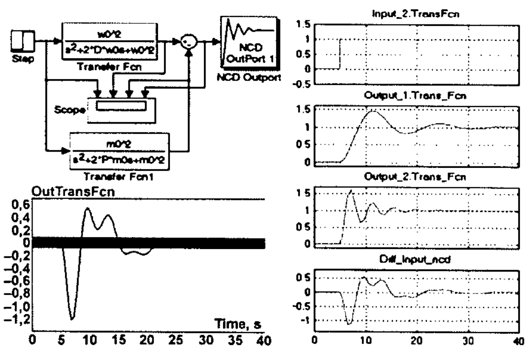
In the help-file for ncd-toolbox is the above mentioned problem discussed and through an example, of a pendulum, solved with two Outport-blocks.

Although we can use several ncd-blocks in a model, there can still appear unstable starting behaviour. Furthermore, when using several ncd-blocks the comparison- and optimization-procedure will not get more transparent.

There is another fundamental problem when working with several output-blocks, namely: they optimize pieces of the model to which they attach but in this process the fundamental parameters for the whole model can get distorted as the tunable variables influence the other ncd-blocks.

This ncd-blocks problem is even more important, when trying to solve simultaneously the identification-problem for two systems. In [13,p.5-9] they state that this is not possible with this version of the program, which might get corrected in later versions.

A simple solution to this multi-block problem was proposed by Prof. Dr. J. Buchholz ("Hochschule Bremen"). The scheme and graphs below explain this solution:



Both in principle identical models (the physical and the mathematical) are coupled in the same way to the input-signal. The similarity of the models is not fully realized as several of the parameters dont correspond to each other, as they are not measurable or have to be defined as approximate guesses.

This can be seen from the above to the righthand-located graphs: the models have different responses (graphs 2 and 3) to the same input (graph 1).

Using the block-adder "Sum" from the Simulink-math-library one could built a difference from both responses as shown in graph 4.

The same difference-graph can be obtained by using "System-outport" by clicking on "options">"initial-response" as can be seen above on the lefthand-located graphs.

In our example shown in the above graph, the upper bop represents a physical model with unknown parameters w_0 and D. The lower loop represents the corresponding mathematical model, whose parameters m_0 and P are chosen from "guessed experience". These m_0 and P parameters should be the tunable variables inserted in the menue: "optimization">"parameters">"tunable variables".

As we wanted to minimize the output difference for the whole time range, we chose the constraint-bounds for the curve to a small range around zero (δ = +/-0.01).

The result for this optimization is shown above as a green line. We inserted the physical model the parameters w_0 = 0.5 and D = 0.25. For the mathematical model we took m_0 = 1.5 and P = 0.15.

After the optimization the program outputs the following values:

>> m_0	m_0 = 0.50
>> P	P = 0.25

With which tolerance were the parameters of the mathematical model determined? The "Optimization Parameters" window offers default values for the tolerance of variables of 0.001 as well as for the deviation from the given constraint-bounds for the curve ("constraint tolerance"), i.e. 0,1%.

For the flight of the autonomous robot one can get also errors in the position, velocity or acceleration. The error in the position, as a deviation from a wanted constant one, is considered as a control error in first degree. If the wanted position changes with constant velocity or acceleration, one speaks of stationary control errors of higher order (2nd or 3rd) [9,p.201]. This is again only valid for small error variables (see point 3, section 5). These important quetions will be followed in a future works.

5. Demands on the Control-Engineering

The purpose of the closed-loop controller is to produce forces and momenta in order to minimize to close to zero the difference between the wanted value (guiding magnitude w) and the actual one (control magnitude x).

If one considers a control for a movement preprogrammed in space and time, the controller should also be realized as a Real Time System.

And now comes the appropriate place to discuss the concept of "Real Time"-System. It is not just a definition per se, but as means to introduce the underlying principles that will fix the axiomatic for projecting our work on the several models. These principles will make it possible to differentiate between systems in "Real Time* and "non-Real Time" for the demands on the control-engineering and its setting of initial conditions.

The computer dictionary cites under Real Time Processing:

"In the real-time-processing one sets precisely the time until which a process should be calculated. For example the real-time for compressing some video material. Important is the real-time-processing mostly in such industries which use robotics. Here the processes are very timely bound so that one needs fast reaction times."

This definition is not precise enought for our purposes and is furthermore controversial, we will try to define another one:

One can divide all technical systems that change their state and/or parameters in time and/or in space into two classes:

a) Systems that have given bounds for all its states and parameters in space and time;
b) Systems that for at least one of their states and/or parameters do not have a given bound in time and/or space.

The first are usual for the processing-industry (PI).

The second are mainly represented in the transport area and can be named "Time-Space-Free-Systems" (TSFS).

Now we can try to fix in words demands for a TSFS-controller:

A controller for a Time Space Free System:

- is in first instance such that it has at least one spatial and/or time non-bounded degree of freedom;
- should not try to control a posteriori points in path, height, velocity and so on, but try to exert with given guiding magnitude w an as small as possible control-difference e. (This is the opposite requirement with respect to the ones in the processing-industry, where a system should not start with the following operation before the previous one has ended completely, independently on the time taken for each step).
- should consider the present movement tendency.

The situation foresees three requirements:

1. The delay of the controller (inclusively reaction time for the final controlling elements) should be smaller than the time-constant of the model (or its parts);
2. The final controlling magnitude ó (and corresponding changes in the final controlling elements) should correspond to the reactive answer of the model (controlled object), thus the final control elements of the controller should produce counter-forces and -momenta with the same function as the response-function of the model on the peifyrbances.
3. The controllers of this kind keep the model uniformly close to the wanted controlling value. This is the main requisite in order to apply the Laplace-transform-method, as the solutions to the equations of motion for flight, only apply for small deviations.

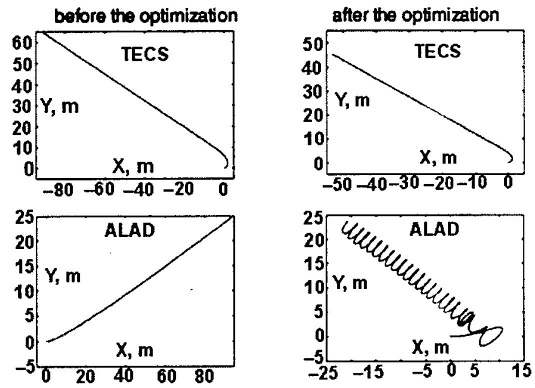
One example in order to ilustrate the above mentioned:

For the parameter identification for the autonomous flying-robot, we made experiments according to the principles of Section 4 (pic.7).

We switched-on two path-schemata tor different models with different parameters to a NCD-Outport.

The purpose was to get close to each other the trajectories for the two models and in this way identify the "unknown" parameters.

In order to avoid the appearance of degenerate equations of motion (correspondingly degenerate parameters) we used slightly different thrust on both sides of the flying models.



One notices directly that the same controller, depending on the initial conditions, behaves as a "time-space-free-system" or a "non-TSF-System", which shows the need for the new definition given above (especially for transport-contolling).

To finalize my short lecture, one can say that despite "...it is very hard, in often contradictory imposed conditions, to find a mathematical formulation for the goodness of a description [7,p. 32]" and "one can never be sure that all the conditions have been considered in their proper relative weight", we can take an optimistic look into the future, as all the above mentioned "only gets proved by the flight experiment".

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CONCEPT OF INTERNATIONAL ROCKET «FIRST AID» FOR THE REMOTE UNINHABITED REGIONS OF THE EARTH

Introduction

Scientific-and-engineering aspects of solution of one of the most humane problems which mankind should decide in the beginning of XXI century were stated. It means a creation of international system of emergency delivery of rescue means for people or objects undergoing a disaster in remote lonely regions of the Earth.

From ancient times to nowadays rocket means were used for organization of celebratory shows, injection of different kinds of signals and delivery of warheads including high-power ones. However rocket means can be used for rescue of people in extraordinary situations too.

At one time C.E. Tsiolkovsky phrased the idea about new sphere of possible use of a rocket technique – for rescue of human civilization by settling a people in Space in a case of threat to life on the Earth for different reasons (approach of global accident, overpopulation etc.). Evolving this idea with reference to earth conditions for the present time, the report considered the scientific-and-engineering solutions of rescue of people fallen in critical situations in remote lonely regions of the Earth, when they cannot rely on "first aid".

During last decades alone there is impressive number of cases, when people fell in extreme situations after, for example, shipwrecks. They perished not having waited till aid comes, as the survival time of people in extreme conditions use to be considerably less time of aid delivery. A "first aid" system with reference to remote lonely regions must have minimal time (tens minutes) and high precision (a few meters) of rescue means delivery.

The solution of major social and technological problems has been achieved by efforts of the leading countries, from medical victories over many illnesses to penetration into outer space. However, a rescue of the people undergoing a disaster in remote uninhabited regions of the Earth remains one of unsolved urgent social problems. By now there are basic technological solutions and appropriate experience of the leading countries, which can ensure a solution of the problem by emergency delivery of rescue means to them for survival. There is a lack of due initiative, international customer and interested investors.

1. Principled Scientific-and-Engineering Solutions

An offered solution of the problem is based on conversion of rocket and airspace means.

Known systems of delivery of rescue means (medicines, food, saving waistcoats, inflatable boats, fuel, communication facilities etc.) are based on use of marine, overland and air vehicles. In the remote regions aid can be delivered by these means, directed by distress signals quite precisely, but during a long time, which can be much more than duration of people's survival under extreme conditions. There are a lot of cases.

The offered system is intended for the fastest delivery, which is possible within the limits of the known physical laws and with high precision. The

characteristics remain the same in a case of rescue means delivery to objects, coordinates of which are known very roughly. High level of main characteristics is reached by combined use of properties of rocket and winged vehicles. Taking into account the great value of human life, the cost of rescue means delivery is not principled.

The global rescue system can be created on the basis of the offered system. The best prototype for use in the system as means of delivery at greater part of approach trajectory to area of a disaster are modern strategic missiles on fixed or mobile launchers, because they have the best alert time (tens seconds). For this purpose the missiles, which are demounted in accordance with international treaties, and artificial satellites of the Earth on low-altitude orbits can be used. However it is impossible to use standard nose cones (NC) of rockets, for example long-range missiles, for delivery of rescue means directly, as their precision of delivery is insufficient (deviation is more than 0,5 km), and the speed of landing is too great (0,5 km/s or more).

A use of the present proposal can serve as example of conversion of a rocket technique, when the most perfect means of destruction will be used for the humane purposes. The Russian Federation patent with the priority of February 8, 1993 was taken out on offered system. The principles of construction of the system and ways of its technical realization were stated also in 23 Royal readings in January of 1999 in Moscow [2].

It is necessary especially to emphasize that it is not simply idea, but new technological solution, which is most close to realization.

2. Scheme of Delivery of Rescue Means

As an alternate solution of the stated problem, rescue means delivery can be effected as follows (fig. 1–3).

A rocket equipped with a special NC starts to disaster region pursuant to target designation coming from disaster region. The fall point of NC is chosen closer to disaster region, as if it flies to a surface on a ballistic trajectory. Before the approach to disaster region at an altitude 2÷3 km with the help of a control system and an elevator, NC is transferred to horizontal flight trajectory. Using a reserve of kinetic energy with a positive angle of attack, NC can fly about 10÷20 km, till the speed decreases to subsonic. After achievement of subsonic speed, NC bottom is separated and with the help explosive pushers the winged rescue-apparatus (RA) equipped with rescue means, propulsion system, e.g. turbofan, guidance system and system of a supplementary reconnaissance of the saved objects is injected. Before RA exit out of NC its wings are compactly stacked. After exit the wings open, the engine starts and RA directs to disaster region. The supplementary reconnaissance system includes a set of sensors of a various physical type (with the purpose to increase probability of detection and identification) for obtaining the current information about anomalies of physical fields, which form by the present people (objects). The supplementary reconnaissance system includes also units of the reference information about anomalies of saved objects, unit of identification and unit of saved people (objects) localization and of decision marking for rescue means separation.

Having come in disaster region, RA executes a supplementary reconnaissance by flight on tack or on a spiral at altitude 20÷50 meters. When preparing flying missions, it is possible operatively to receive the information from databases of global geoinformation systems about the disaster region surface (relief, snapshots in various wave bands, object structure etc.), necessary for RA high-precision navigation. Taking into account, that rockets of the rescue system will be based in various regions of the Earth (for example, on bases or near to bases of strategic missiles, on islands, on submarines etc.), the safe areas of fall of fulfilled stages of the rockets in each particular case can be found by selection of proper form of a trajectory and by selection of appropriate rocket site. If in region of catastrophe the special buoys radiating in radio or IR bands will be thrown out, then, under the data of direction finders, RA will be brought to them by a homing system with high precision. The localization and decision marking unit drops the rescue means to the identified objects adjusted for a drift by the data of the identification unit. The precision of dropping can make from several meters up to tens meters.

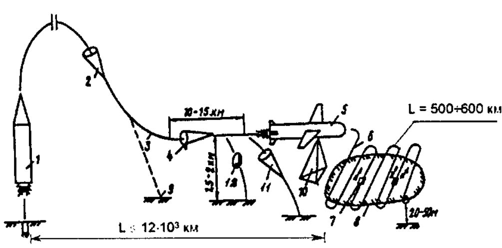

Fig. 1. The scheme of delivery of rescue means: 1 – rocket, 2 – nose cone, 3 – segment of transition, 4 – control flap, 5 – winged rescue-apparatus, 6 – search trajectory, 7 – objects of rescue, 8 – disaster area boundary, 9 – fictitious aiming point, 10 – directional diagram of navigation and supplementary reconnaissance means, 11 – heat-shielding body, 12 – bottom.

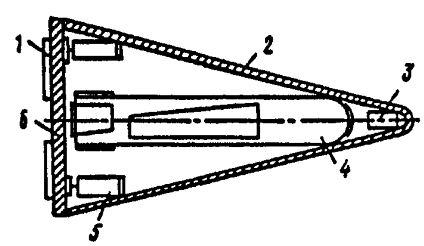

Fig. 2. The scheme of layout of a nose cone: 1 – bank control, 2 – heat-shielding body, 3 – explosive pusher for RA injection, 4 – RA with folded wings and control surfaces, 5 – explosive pushers for bottom separation, 6 – bottom.

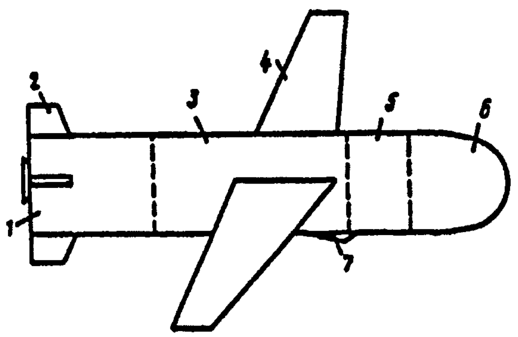

Fig. 3. The aerodynamic scheme and constituents of the winged RA: 1 – propulsion system, 2 – control surfaces, 3 – rescue means, 4 – wings, 5 – guidance system, 6 – supplementary reconnaissance means, 7 – air intake.

The rescue means can be dropped with "soft" touchdown in one point or in several points, if the objects of rescue are identified in them. Depending on character of disaster, there can be some standard sets of rescue means. It is natural, that some rescue means, for example, buoyancy belts, boat etc., should be prepared for service automatically.

After job processing it is possible to splashdown or to land RA with the help of a parachute system for its reuse, similar at e.g. cruise missiles tests. Concerning supplementary reconnaissance sensors used in the system, it is necessary to note, that to the present time their sensitivity is high enough with acceptable weight-dimension characteristics. There are extremely favorable conditions for activity of the supplementary reconnaissance system (low level of flight, subsonic speed, not heated body, capability of obtaining of information through optical, radio and magnet transparent inserts).

Some approximate estimation for the NC weighing 1 ton:

weight of the winged RA: approximately	750 – 800 kg;
weight of supplied rescue means:	250 – 280 kg;
weight of guidance system:	80 – 100 kg;
weight of anomaly sensors:	60 – 70 kg;
weight of propulsion system:	140 – 150 kg;
weight of glider:	170 – 200 kg;
RA range ability:	500 – 600 km.

3. About Creation of a Global System of Rescue Means Delivery

The offered aeroballistic system can be a basis for creation of a global system of emergency delivery of rescue means for people and objects in remote regions. The global system of emergency delivery of rescue means should include a subsystem of distress calls reception, e.g. KOSPAS-SARSAT, and a subsystem of notification of all interested states having early warning systems, anti-aircraft or antimissile systems.

The global system could use elements of battle means for fulfillment of the highly humane purpose. Such systems can maintain only rocket powers, in common or under aegis of the UN. It means that the global system of emergency delivery of rescue means should be international. It concerns questions of creation, financing and operation. Even separate super-powers or group of states are able to construct the system of global rescue on the basis of the offered aeroballistic delivery system, because there are hundreds of missiles under reduction of armaments or under ending of their operation term to be removed, whereas for creation of a rocket grouping of rescue it is necessary tens launchers, as the large disasters happen not so frequently. The main design and scientific efforts should be directed on creation of NC, automatic RA and their sufficiently complex artificial intellect (AI) systems.

Quite definitely, Russia has got a serious scientific-and-engineering and industrial experience for creation of the offered system. There are necessary scientific-and-engineering staff and industrial organizations, which are capable to execute the whole business. It must be stressed especially, analogs of the majority of constituents of the system are probed and spent, when various means of scientific, military, social and economic assignment were created. So, a fast realization of the system from the scientific and industrial standpoints is beyond any doubt. Necessity of the offered rescue system and expected powerful effect from its application are obvious.

4. Organizational Problems of System Researches and Engineering

Certainly, political agreements reinforced by technological solutions to exclude suspicions of missile attack under the pretence of RA start should precede a creation of such global rescue system. The system creation has definite moral-ethical value, as the basic elements of the most powerful weapon created by mankind begin to play the most humane role – a people's rescue in extreme situations.

In the time of RA creation, which is, in essence, the flying robot, it is expecting very serious scientific achievement in the field of development of the original aerodynamic schemes of RA, advanced sensors of physical fields, intellectual information technologies and AI systems with a broad set of functions, which till now were executed only by man when rescue means deliver. These achievements exceed far the limits of the soluble problem and can have unpredictable scope of applications.

The raised proposal can be used as a basis for a technological development program of emergency delivery system of rescue means and freights in remote regions of the Earth to people undergoing a disaster. A basis of the system can be ballistic missiles, first of all, heavy ones.

The ministries on extraordinary situations of the leading countries of the world and Russia could be customers of the offered system on the initial

stages of full-scale studies. One of international organizations, e.g. the International Red Cross, under aegis of the UN could be customers on subsequent stages.

As a developer of the system the leading space-rocket firms having appropriate experience and business authority in the world could act. The financial basis for realization of the project can be the contribution of the system development participants, expected gains from the system users and bank investment.

5. Conclusion

In conclusion it would stress, that the people going on risk in the name of general purposes or fallen in trouble as fate willed it in remote regions of the Earth have the right to expect to civilization aid. It is necessary to think that the human community at the present stage of evolution can allow it to itself. The said will not show rhetoric at all if one fancies hopeless situations the people fall in extraordinary conditions. The described rescue system like, figuratively speaking, longest and fast hand of first aid will be created early or late. And the sooner, the more sure and safe people working in remote and desert regions of the Earth will feel.

There is a basis to believe, that human community in the first half of second decade XXI century will create space-rocket "first aid", as for this purpose there are all technological reasons now. Assuming, that community of the Earth will find the financial resources, political-military aspects of the problem can become a stumbling block, on our sight. These difficulties can be overcome on a basis of mutual trust of the leading states and readiness to aid gratuitously the people fallen in extreme situations in remote lonely regions of the Earth.

References

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2. G.G. Vokin Evolution of Rocket Rescue Equipment (From Ancient Rockets to Modern Aeroballistic Systems). Thesis of Report on the 23 Scientific Readings on Astronautics. Moscow, 1999.

Session II

PROBLEMS OF HIGH TECHNOLOGIES COMMERCIALISATION AND INTERNATIONAL COOPERATION

Dr. Sergei L. CHERNYSHEV
Deputy Director of TsAGI for International Business Development
Expert in Aeronautical Sciences and Aviation.
Ph.D. degree in Aeronautics.

Education:	1995	University of Michigan Executive Program at the School of Business Administration.
	1978 – 1981	Ph.D. Program at Moscow Phys Tech. (Computational Fluid Dynamics (CFD).
	1972 – 1978	Moscow Phys Tech, Aerospace Engineering degree.
Employment:	1997	present TsAGI, Deputy Director.
	1993 – 1997	Central Aerohydrodynamic Institute (TsAGI), Special Advisor to the Directorate, responsible for International Business Development.
	1981 – 1993	TsAGI, Aerospace Engineer; Research Scientist; Senior Research Scientist; Head of Applied Aerodynamics Research Department.

AEROSPACE R&D MARKETING: TsAGI EXPERIENCE

AEROSPACE R&D MARKETING: TsAGI EXPERIENCE

Presented by: ***Dr. Sergei Chernyshev,***
Deputy Director International Business Development

International Conference
June 8 – 9, 2000
Berlin, Germany

THE PAST

- First Interest in International Business Development 1990
- First Contacts
- Marketing was Very New to Russian Companies – Very Basic Approach
- 1993 Traveled and Lived in U.S.

REVIEW OF KEY OBJECTIVES & CRITICAL SUCCESS FACTORS

- What makes company unique
- What makes company successful
- What is our product
- Shared vision of our mission
- Review key undertakings of past year

MAIN AREAS OF EXPERTISE

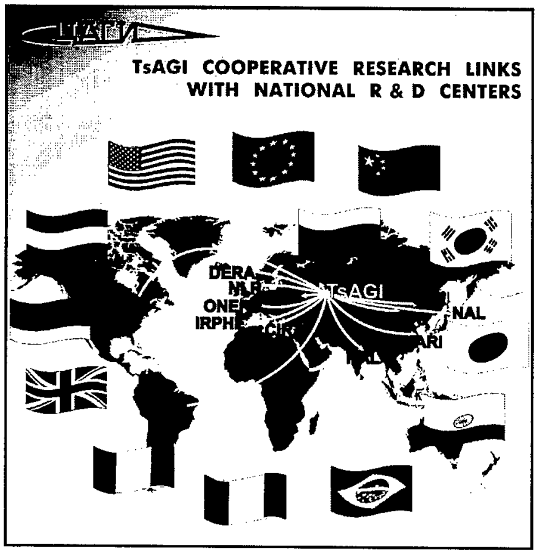
- Aeroacoustics
- Aerothermodynamics & Gas Dynamics
- Aerodynamics & Hydrodynamics
- Aircraft Certification & Flight Testing
- Aircraft Propulsion
- Aircraft Strength & Structures
- Alternative Energy Sources
- Atmospheric & Environmental Research
- Computer Science
- Experiments Facility Development
- Flight Dynamics & Control Systems
- Flight Simulation & Pilot Training
- Industrial propellers & fans
- Lasers & optics
- Holography
- Microwave Technology
- Plasma Physics
- Precision Manufacturing

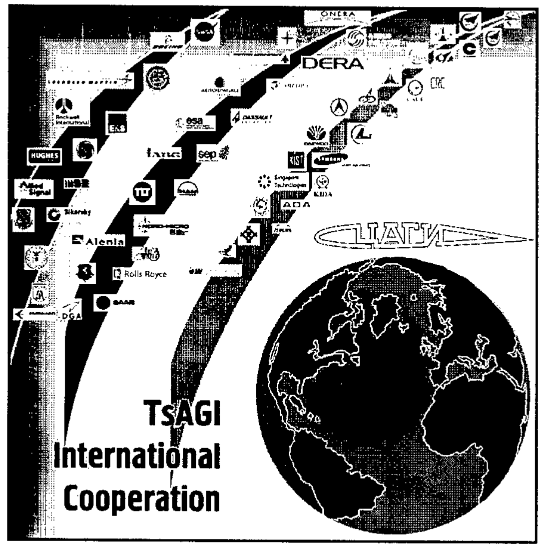
TsAGI MARKETING APPROACH

- Establish a physical presence in selected countries.
  - Presents professional image
  - Improves communication links
- Joint Venture Programs
  - Increase Corporate Capabilities
  - Wider Market Accessibility
  - TsAGI Leadership in Joint Efforts

MAIN ACHIEVEMENTS IN INTERNATIONAL COOPERATION

- Over 250 R & D Contracts
  - Leading edge technologies
  - Unique testing
  - Specialized task-oriented software
  - Conceptual design
  - Project technical evaluation etc.
- Over 50 International Customers
  - Aerospace Corporations
  - Non-Aerospace Industry Companies
  - Scientific Research Centers
  - Universities & Scientific Research Labs
- Different forms of Cooperation
  - Contracts
  - Grants
  - Conferences
  - Exhibitions
- High Level of Technical Expertise
- High Level of International Business Management
- Well Recognized in Russia & Abroad





FUTURE
Primary Marketing Factors

- Visual - Face to Face contact
- Printed Materials - Advertising
- Reputation - Image, Work Ethics
- Product - Needs of Industry
- Globalization of Aerospace Business

Survival depends on constant improvements in marketing approach.

GOALS FOR THE MILLENIUM

- TsAGI – Russian Aerospace Community
- Strengthen International Alliances

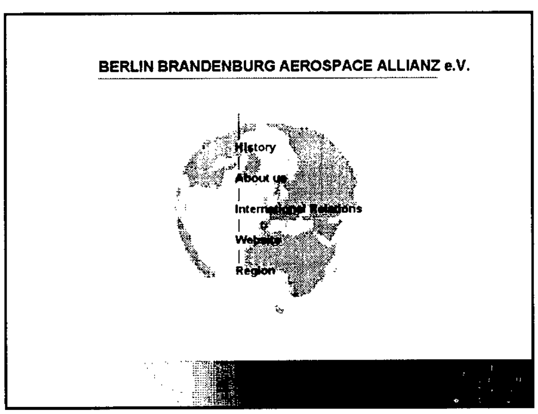
Andreas KADEN
Managing Director,
Lufthansa-Bombardier Aviation Services Gmbh, Germany

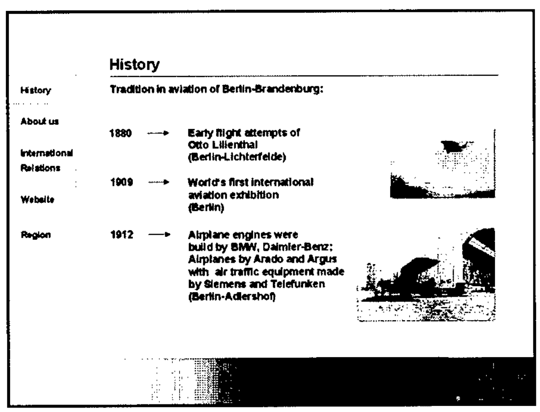
BBAAc.V.

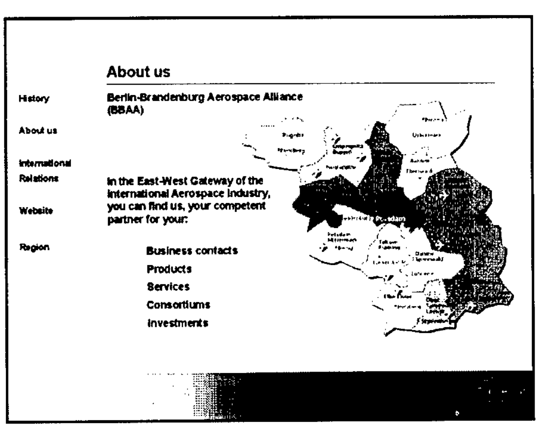
STRATEGIC BRANCH ALLIANCES – A STEP IN THE DIRECTION OF CONSTRUCTING COMMON SUCCESS

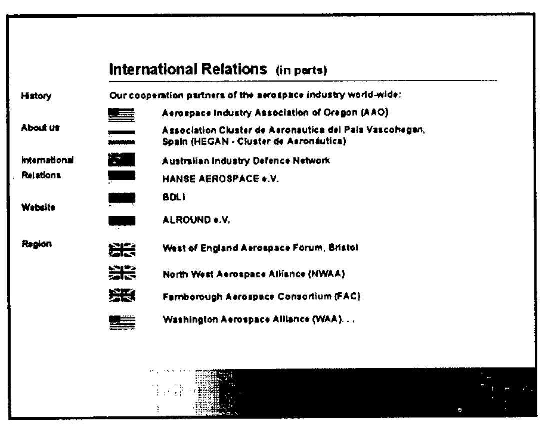
Business and industry in the Berlin/Brandenburg region are expanding rapidly. The aerospace industry is playing an important role in this growth and is extraordinary supported by the regional administrations. Global players such as Rolls-Royce Germany, MTU, Lufthansa and Bombardier have made a wise decision in investing in this promising economic region.

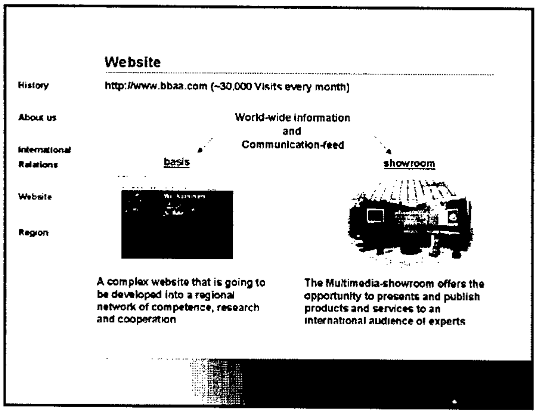
The main targets of BBAA are the construction of networks of cooperation in regional and international aerospace production fields, in research and technology developments, subcontractors and finally the care of tradition of a cradle of germans aircraft industry.

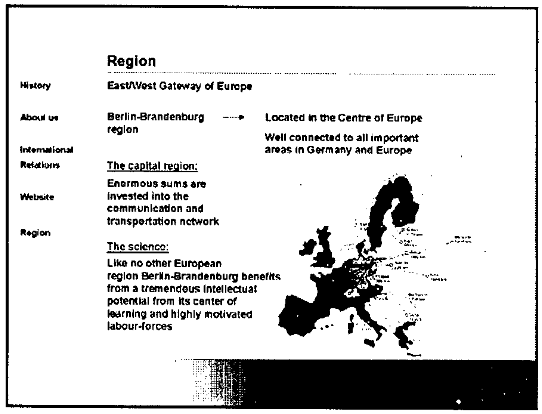









Website
History
About us
International Relations
Website
Region
http://www.bbaa.com (~30,000 Visits every month)
World-wide information
and
Communication-feed
basis
showroom
A complex website that is going to be developed into a regional network of competence, research and cooperation
The Multimedia-showroom offers the opportunity to presents and publish products and services to an international audience of experts


Region
History
About us
International Relations
Website
Region
East/West Gateway of Europe
Berlin-Brandenburg region
Located in the Centre of Europe
Well connected to all important areas in Germany and Europe
The capital region:
Enormous sums are invested into the communication and transportation network
The science:
Like no other European region Berlin-Brandenburg benefits from a tremendous intellectual potential from its center of learning and highly motivated labour-forces

Hervé CONSIGNY

ONERA

Hervé Consigny studied Mechanical Engineering at Ecole Centrale de Lille, France and graduated in 1975. He then joined the Von Karman Institute for Fluid Dynamics in Rhode-St-Genèse, Belgium for a postgraduate work on both experimental and computational aspects of Heat Transfer onto Aeronautical Turbine Blades which led to the award of PhD in Applied Sciences at the Bruxelles's University in 1980.

In 1980 Hervé Consigny joined the Applied Aerodynamics Division of ONERA where he was responsible for research in the field of unsteady aerodynamics associated to the motion of control surfaces. In 1984 he was posted to the Experimental Aerodynamics Division in charge of operating six aerodynamic research wind tunnels located in Meudon near Paris covering a Mach number range from 0.2 to 10 and of developing the corresponding measurement and testing techniques. He became Head of that division in 1989. During that period, Hervé Consigny also delivered lectures in Fluid Mechanics (Boundary Layers, Heat Transfer, Measuring Techniques) at several French Engineering institutions. Hervé was also the ONERA representative to the Supersonic Tunnel Association (STAI) from 1990 to 1993.

In 1994 he joined the ONERA International Affairs department as Assistant Director and became director in 1999.

Hervé has three daughters and his interests include the countryside, scuba-diving and small-scale models of aeroplanes and trains.

A SHORT OVERVIEW OF THE ONERA-TSAGI PAST AND PRESENT COOPERATION

Abstract

The presentation aims at providing a short overview of the past and present co-operative activities between ONERA, the French National Aerospace Research Establishment and TsAGI, the Central Aerohydrodynamics Institute of Russia.

Indeed, both research establishments have a long tradition of relationship in the field of aeronautics: in the past, through contacts initiated forty or so years ago and established in the framework of various institutional mechanisms and more recently, through direct bilateral and multilateral co-operative projects.

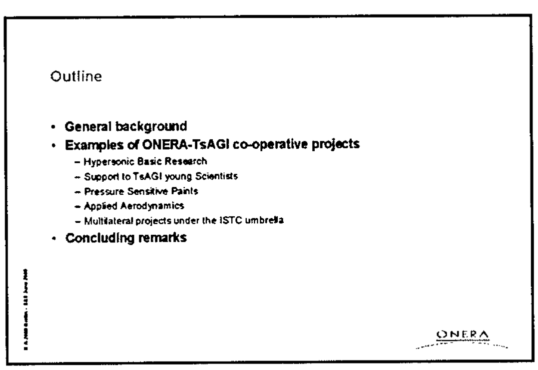
Examples of such recent projects in the field of fundamental and applied aerodynamics as well as in the field of new instrumentation techniques are provided. The main scientific results so far obtained are briefly commented. In addition and on the basis of the available experience, this presentation will also provide an analysis of some of the difficulties encountered in conducting these various actions. Tracks for improvements are suggested.

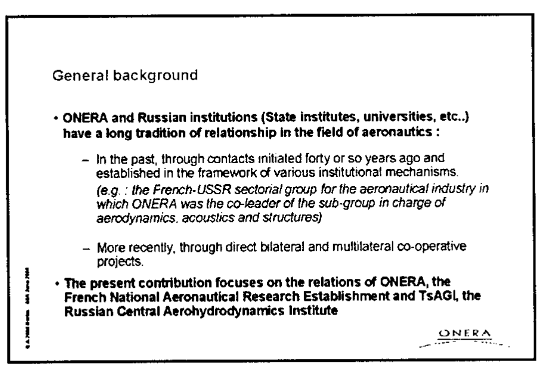
These examples illustrate that this type of actions obviously results in an overall benefit in several respects for both the ONERA and the TsAGI aeronautical research community and that the effort should be pursued.

1. Introduction (viewfoil # 3)

ONERA and Russian institutions (State institutes, universities, etc..) have a long tradition of relationship in the field of aeronautics :

- In the past, through contacts initiated forty or so years ago and established in the framework of various institutional mechanisms like for example the French-USSR sectorial group for the aeronautical industry in which ONERA was the co-leader of the sub-group in charge of aerodynamics, acoustics and structures and which led to several reciprocal visits of delegations.
- More recently, through direct bilateral and multilateral co-operative projects in various frameworks.





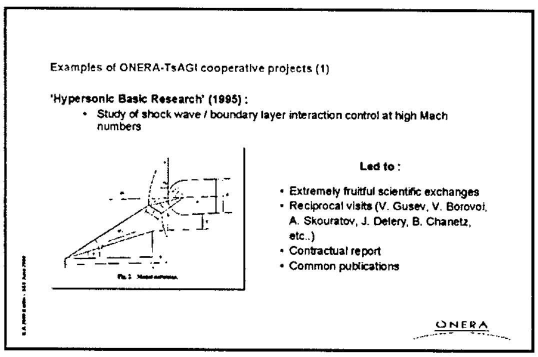
Concerned Russian institutions are the Moscow Aviation Institute (MAI), the Central Institute of Aviation Motors (TsIAM), the University of St. Petersburg, the Institute of Theoretical and Applied Mechanics of Novosibirsk (ITAM), the Institute of Thermophysics of Novosibirsk, the Russian Academy of Sciences (RAS).

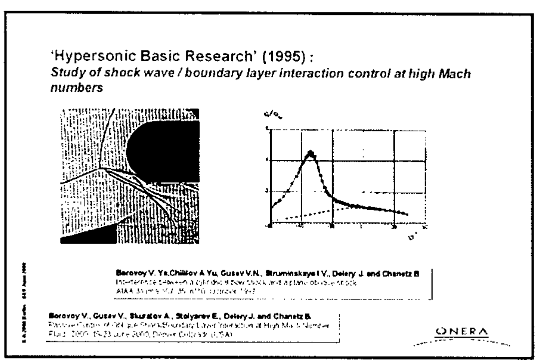
The present presentation does not aims at providing an exhaustive description of all these relations but simply focuses on the particular partnership between ONERA, the French National Aeronautical Research Establishment and TsAGI, the Russian Central Aerohydrodynamics Institute.

2. Examples of ONERA-TsAGI co-operative projects

2.1. Hypersonic Basic Research (1995) (viewfoils # 4 and # 5)

It is well known that one of the mot challenging problem of gasdynamics is shock/shock and shock/boundary layer interference. The study of such a class of problems is of a great interest for practical applications and is indispensable for understanding heat transfer mechanisms on a hypersonic vehicle surface. For this reason, a collaborative fundamental activity study of shock wave/boundary layer interaction control at high Mach numbers was set up between ONERA and TsAGI with the financial support of the "Direction de la Recherche et des Etudes Techniques" of the French Ministry of Defence. This co-operation dealt with an extensive experimental investigation and with the collection of a large quantity of data under different flow conditions. This resulted in a comprehensive documented database for validation of computation methods.



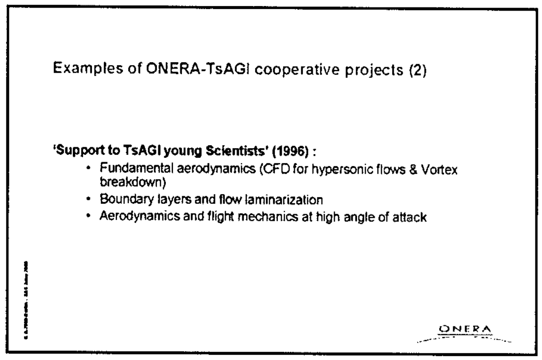


These extremely valuable set of fundamental results lead to common publications and there is no doubt that the fruitful scientific exchanges complemented with several reciprocal visits were mutually beneficial. For these several reasons it is the author's opinion that this co-operation was exemplary in many respects.

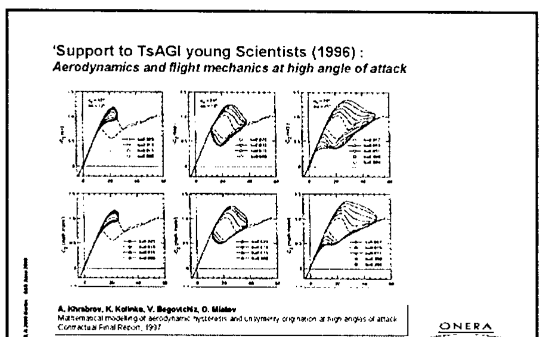
2.2. Support to TsAGI young Scientists (1996) (viewfoils # 6 and # 7)

On purely institutional ONERA funding, the following three topics were considered in 1996 to be important to deal with, in the frame of a voluntary action to support TsAGI young scientists.

- Fundamental aerodynamics (CFD for hypersonic flows & Vortex breakdown)
- Boundary layers and flow laminarization
- Aerodynamics and flight mechanics at high angle of attack



It is clearly not the purpose of this contribution to provide a comprehensive description of the scientific work that was achieved in the three domains. As an illustration of this co-operation, the figures of viewfoil # 7, which is extracted from the contractual document entitled "Mathematical modelling of aerodynamic hysteresis and unsymmetry origination at high angles of attack". The work has demonstrated that the very complex phenomena of three dimensional separated flow can be described – at least qualitatively – with the use of simple non-linear mathematical models.



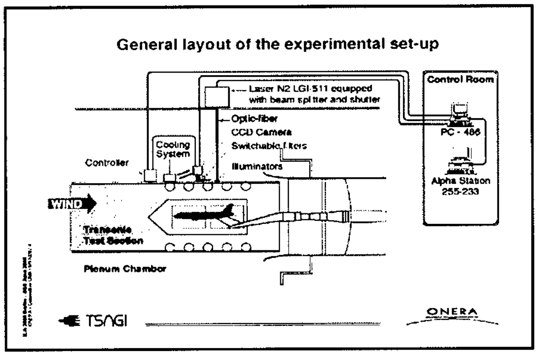
2.3. Pressure Sensitive Paints (1995 – 1998) (viewfoils # 8 to # 11)

It has been well recognized since many years that Pressure Sensitive Paints (Luminescence Pressure sensors according to the TsAGI termi-

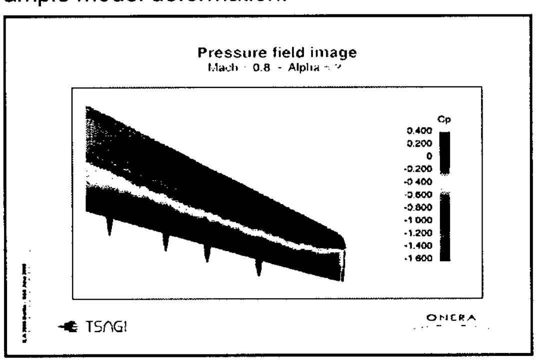
Examples of ONERA-TsAGI co-operative projects (3)

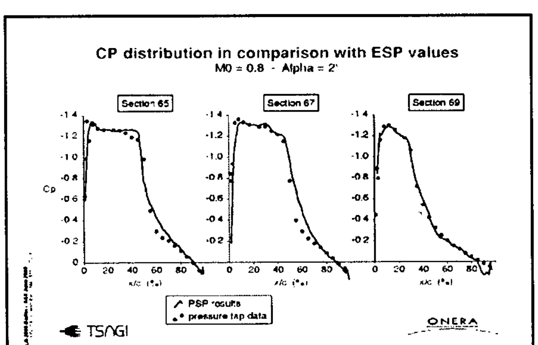
'Pressure Sensitive Paints' (1995 - 1998) :
- Test of an ONERA model in the TsAGI / T.106 wind tunnel
- Complementary test campaign in the ONERA / S2MA wind tunnel
- Purchase of a complete TsAGI system for ONERA / Modane wind tunnels

ONERA



nology) was a potentially promising measurement technique which permits remote model surface pressure measurement in an aerodynamic wind tunnel with several advantages. However, the setting up of such a technique in industrial environment suffers from two major difficulties: the first one relates with the paint itself and the second one relates with the sophisticated data reduction software which should take into account both the physics and the complicated problem of accurate digital image processing which has to take into account a number of parasite effects like for example model deformation.





In early 1995 it was decided to join ONERA and TsAGI efforts on this topic. The first step consisted in a detailed evaluation of the TsAGI basic technology in transonic conditions and for this purpose, an ONERA model in the TsAGI/T-106 wind tunnel was tested under a specific ONERA contract.

The very encouraging results obtained in T.106 were then confirmed during a complementary test campaign in the ONERA/S2MA wind tunnel at the end of 1995 so that it was rapidly decided to purchase a complete TsAGI measurement system for ONERA/Modane wind tunnels.

Nowadays the measurement technique which has received – from the ONERA point of view – significant improvements in particular with respect to sophisticated data reduction procedures is in a position to fulfil the need of industrial customers is considered to be operational in the Modane transonic facility. This co-operative activity has to be considered as a success even if some difficulties are still encountered concerning the maintenance of the illumination system.

2.4. Applied Aerodynamics (viewfoils # 12 and # 13) :

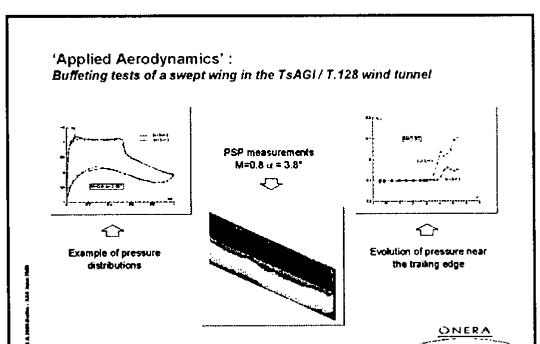
For transport aircraft, the onset of buffeting still remains an important problem. Although some progress has been made, this phenomenon cannot be predicted in a reliable way at the present time. For this reason, in addition to a French national programme on this particular topic, a proposal initiated by Dassault has been prepared by ONERA in agreement with the French Official services to conduct an experimental project in the TsAGI/T-128 facility. The project included the manufacturing of a specific model upon ONERA specifications.

The first test campaign was performed in September 1998 in order to validate the experimental

Examples of ONERA-TsAGI co-operative projects (4)

'Applied Aerodynamics' :
- Buffeting tests of a swept wing in the TsAGI / T.128 wind tunnel (two test campaigns - September 1998 & November 1999)

ONERA



set up and to perform steady states measurements as well as preliminary unsteady measurements. The second test campaign which took place in November 1999 concentrated on complementary detailed unsteady data and on Pressure Sensitive Paints technique.

This operation is already considered as a success from the ONERA point of view.

2.5. Multilateral Projects Under the ISTC Umbrella (viewfoils # 14 to # 18)

ONERA has been involved several times in INTAS projects. ONERA has also been taking part in a certain number of projects conducted under the International Science and Technology Centre (ISTC) since 1995. Among them are the following:

- Development of new methods for laminar flow control and drag reduction
- Ecological aspects of the impact of a supersonic civil aircraft of the second generation on environment
- Investigation of aircraft vortex wake evolution and flight safety
- Development of methods for calculating shapes of ice formations and their impact on aerodynamic characteristics stability
- Optimization of 3-D components and integrated configurations of supersonic aircraft
- Flight safety, aircraft vortex wake and airport operation capacity (in relation with EU/Wavenc project)

Examples of ONERA-TsAGI co-operative projects (5)

Multilateral projects under the ISTC umbrella :

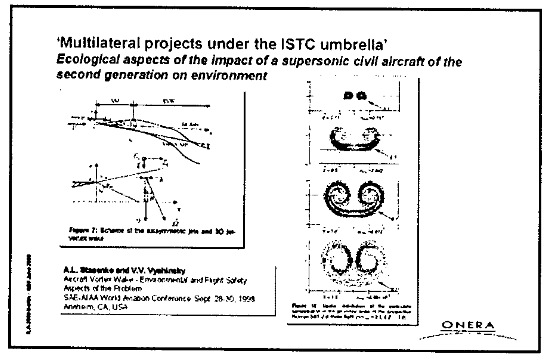
- Development of new methods for laminar flow control and drag reduction.
- Ecological aspects of the impact of a supersonic civil aircraft of the second generation on environment.
- Investigation of aircraft vortex wake evolution and flight safety
- Development of methods for calculating shapes of ice formations and their impact on aerodynamic characteristics stability.
- Optimization of 3-D components and integrated configurations of supersonic aircraft
- Flight safety, aircraft vortex wake and airport operation capacity (in relation with EU/Wavenc project)

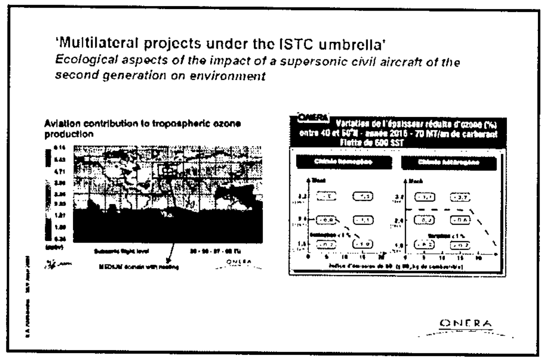
ONERA

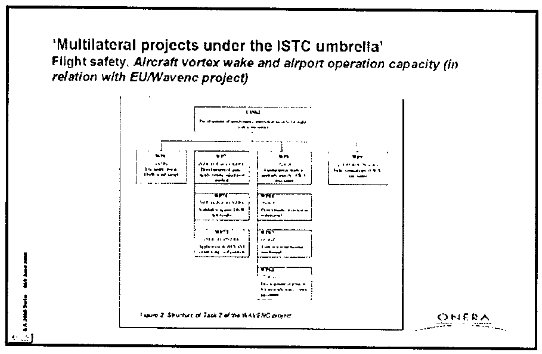
In addition ONERA participated in the evaluation of a number of proposals and recommended several new projects in this framework.

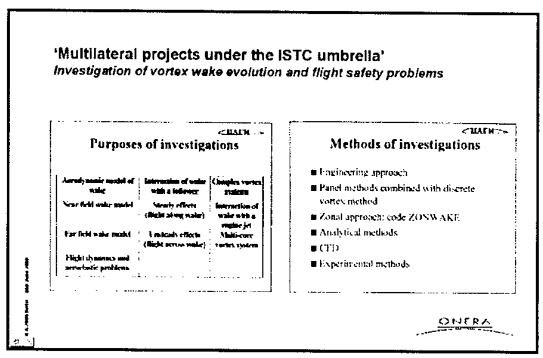
It would be difficult through the present contribution to provide a comprehensive description of all concerned projects. It might be however worthwhile to point out the extremely large amount of work performed under ISTC contract devoted to "Ecological aspects of the impact of a supersonic Aircraft of the second generation". The valuable results that were obtained were used by the entire scientific community involved in environmental problem for prospective studies.

The second project which also retained a considerable interest of ONERA scientists was the one dealing with "Flight Safety and Aircraft vortex wakes" which lead to the participation of TsAGI in the EU WAVENC project with the leadership of Work Package # 8 (Fundamental Study of Unsteady Aspects of Wake Vortex encounter) and the essential participation in Work package #7 in co-operation with ONERA, Aerospatiale and the Dutch NLR.





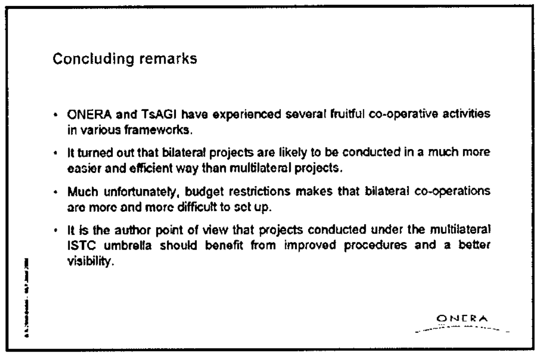




3. Concluding Remarks

ONERA and Russian institutions, in particular TsAGI, have experienced several fruitful co-operative activities in various frameworks. It is considered that all these activities have been globally mutually beneficial and have served to reinforce scientific and technical knowledge as well as confidence between respective teams.

As usual, it was again noticed that bilateral projects are likely to be conducted in a more much easier and efficient way than multilateral projects. But (much unfortunately) budget restrictions and (may be fortunately) globalisation make that the tendency is to set up more and more multilateral and somewhat complicated partnership. As far as framework like for example ISTC are concerned, it is the author point of view that improved procedures and better visibility should be looked for.



Dr. Adriaan de GRAAFF

Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Mr. De Graaff was born in Voorburg, the Netherlands in 1949. In 1973, he received his Master Degree in Economics and Business Administration at the University of Groningen.

During 1972-1973 he worked at that University.

From 1973-1982 Mr. De Graaff held a staff position a NLR, the National Aerospace Laboratory. Apart from issues related to the NLR financial policy, he was engaged in setting up the German Dutch Wind Tunnel (DNW), a German-Dutch joint venture. In 1982, he became Secretary-Treasurer of the Board of NLR being responsible for, amongst others, government relations. In 1992, Mr. De Graaff became Associate Director of NLR, responsible for corporate strategy and European affairs.

Mr. De Graaff was involved in setting up EREA, the association of European Research Establishments in Aeronautics in 1993 and has been a member of the Strategy Group/Executive Secretariat since the start. He also chairs the Aeronautical Research Group (ARG), which represents the liaison of EREA with the European Commission and the European industry. Within EREA, Mr. De Graaff is member of several networks like on aviation safety and wind tunnels.

Mr. De Graaff was co-founder of the Dutch Military Aviation Museum and was a political advisor on defence issues to one of the major Dutch political parties in the parliament from 1982 till 1998.

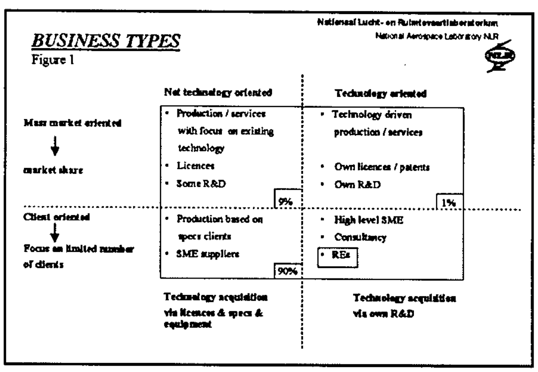
In 1998, he was elected as member of the Town Council in his hometown Delft. Mr. De Graaff held a private pilot licence.

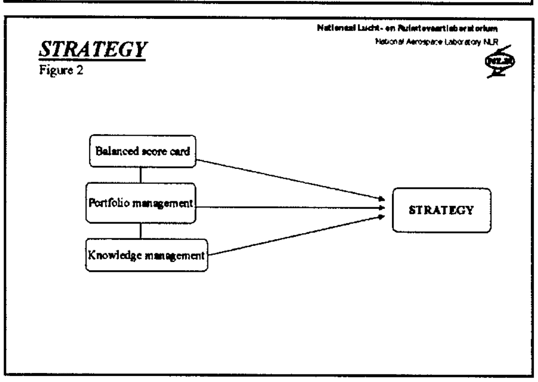
Mr. De Graaff is married and has one son.

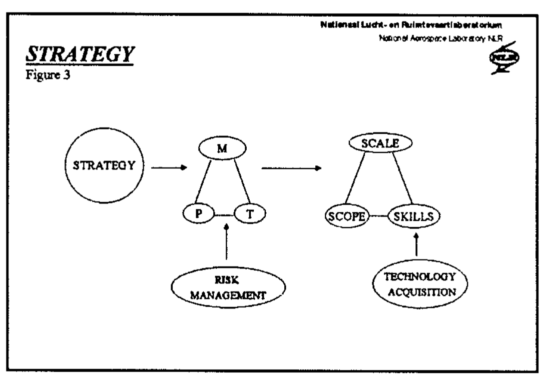
NLR EXPERIENCE IN INTERNATIONAL COOPERATION

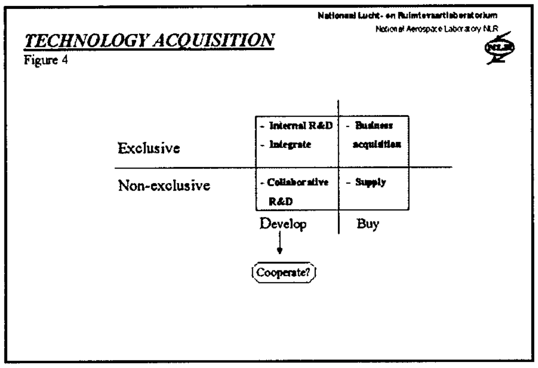
Globalisation in the aviation sector urges the research infrastructure to develop alliances amongst themselves. This requires alliance management to choose those partners for collaborative efforts that will create the best win-win options in cooperation. Alliances will not only have to be aimed at creating added value in technical knowledge (skills), but can also provide new opportunities for the development of new joint products and services as well as to create new joint market opportunities.

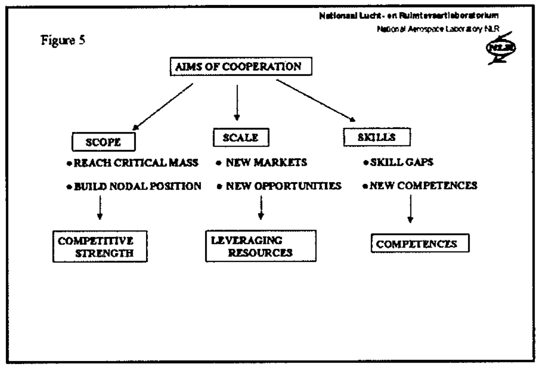
Structural and relationship issues are determining the success or failure of alliances: the right chemistry and trust are essential elements for fruitful cooperation. In Western Europe, research establishments have already embarked on a process of creating structural alliances and mergers. This activity could be expanded towards Russia. Past NLR experience of cooperation with Russian organisations has been limited but there are good examples where the cooperation has been very successful. Financial incentives help to develop new relationships, and new opportunities under the 6th Framework programme should be created to stimulate the cooperation with Russian organisations in aeronautical research.

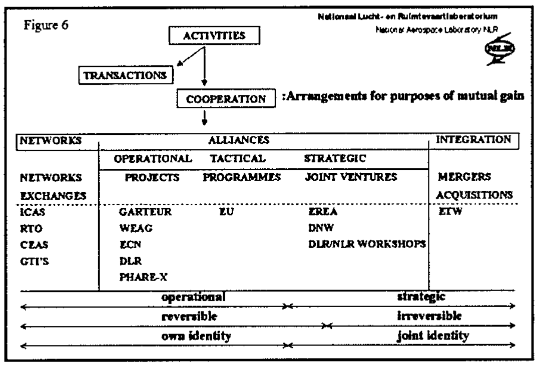












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National Aerospace Laboratory NLR

Figure 7

OVERALL BUSINESS EXPERIENCE:

30% of alliances succeed

70% fail due to : - structural issues (30%)
- relationship issues (70%)

(KPMG)

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National Aerospace Laboratory NLR

Figure 8

PROCESS (1)

STRUCTURAL ISSUES

- ✓ Partner perspectives / interest
- ✓ Complementary / competences
- ✓ Market position
- ✓ Financial position
- ✓ Turnover
- ✓ Management style
- ✓ Timing

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National Aerospace Laboratory NLR

Figure 9

PROCESS (2)

RELATIONSHIP ISSUES

- ✓ Chemistry
- ✓ Commitment
- ✓ Personal fit
- ✓ Trust / honesty
- ✓ Culture / mentality
- ✓ Loss of face
- ✓ Language

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ALLIANCE MANAGEMENT

Figure 10

- ✓ Use experience
- ✓ Emphasize chemistry
- ✓ Preparation
- ✓ Reflection
- ✓ Communication
- ✓ Evaluation criteria

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Figure 11

ROADMAP

1. INTERNAL

- → Why (objective - 3S: scope, scale, skills)
- → SWOT
- → Partner programme (corporate, major, minor partners)
- → Market overview (dynamic list)
- → Portfolio management (which - conflicting - alliances)
- → What we want (diversity in counsel, unity in command)
- → Evaluation criteria
- → Team selection (deal teams)
  - → Executive sponsor
  - → Core team (departments + financial)
  - → Legal team
  - → Support team (driver)

Figure 12

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ROADMAP (2)

2. EXTERNAL

A. Scoping
- → **Meeting of executives → creative ideas**
- → **Team visits**
- → **Collaborative list**
- → **Final listing → joint business**

B. Contracting
- → **Joint business plan → use deal teams (incl. Executive sponsor)**
- → **Reflection : success parameter score card**

C. Agreement

D. Implement + manage + develop

Figure 13

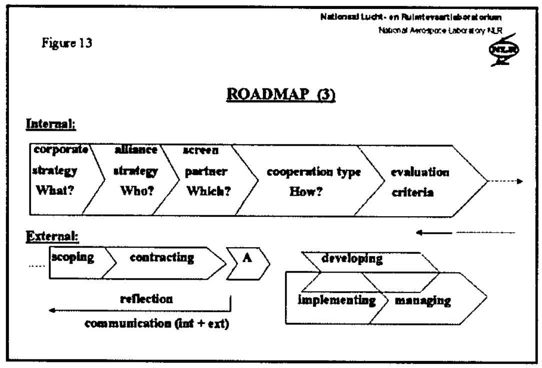

Figure 14

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ORGANISATIONAL

STRATEGY
- Joint strategy
- Clear communication
- Rules to enter / exit

STRUCTURE
- Responsibilities
- Balance of power
- Internal support

SYSTEMS
- Company support
- Share information
- Budgetting

TARGETS / PLANS
- Joint targets
- Project plan
- Indicators
- Benchmark

CULTURAL

CULTURE
- New culture
- Awareness cultural issues
- Payment systems

COMMUNICATION
- Openess
- Trust
- Feedback to all concerned

LEADERSHIP
- High level position
- Management capabilities of cooperation
- Involvement

TRUST
- Joint learning
- Joint development
- Feedback
- External help

MANAGEMENT

POLICY SUPPORT
- Context
- Portfolio
- IPR

COMMUNICATION
- Inside
- Outside

INSTRUMENTS
- Join knowledge
- Practical experience

CONTROL
- Keep score cards
- Portfolio analysis

Examples of Russian/NLR cooperation

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

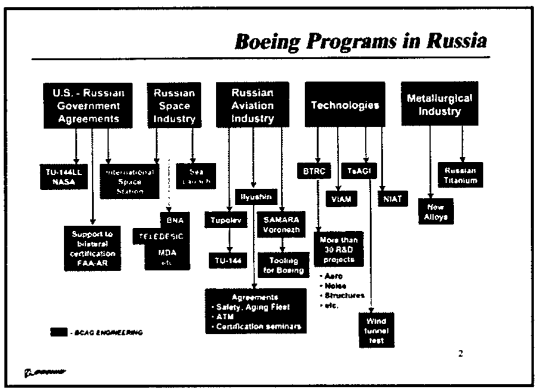
Figure 15

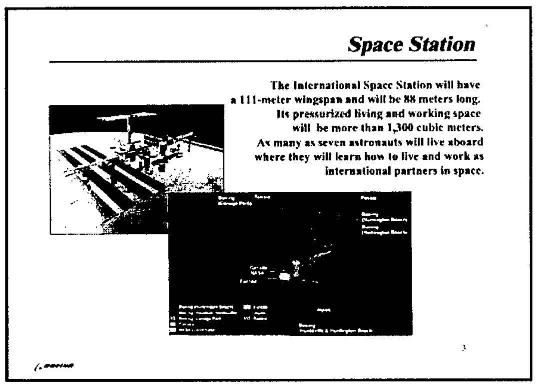
Past
- **CEAS contacts**
- **Visits**
- **Symposia - AGARD/RTO (wind tunnels)**
- **Short courses of Bank for Eastern Europe on environment near airports**
- **ISCT** - **Review of proposals (microgravity)**
  - **Cooperation effort 201 - Wake vortex (TsAGI)**
  - **199 - Laminar flow (TsAGI)**
  - **200 - Environmental impact SST (TsAGI)**
  - **627(Pt. 1&2) - Airborne monitoring (Gromov)**
  - **1551 - Aircrew information (TsAGI)**
  - **... - Crew decision support (Gromov)**
- **INTAS** - **Heat Mass Transfer (Ukraine 95 - 196)**
- **EU-Framework** - **WAVENC (Wake Vortex Modeling) - TsAGI**
- **Potential staff training (under discussion)**

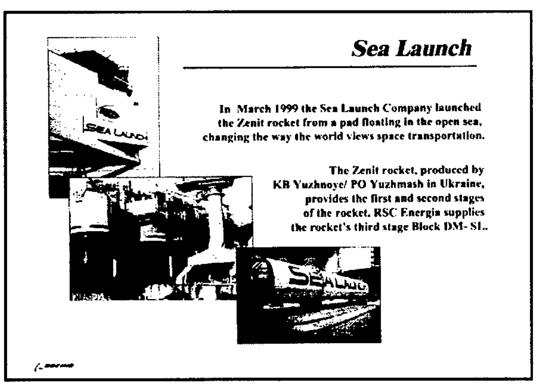
Matthew J. BENCKE
Individual Consultant to the Boeing Company

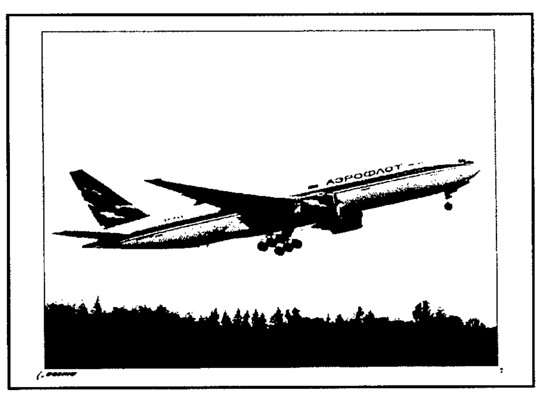
BOEING®

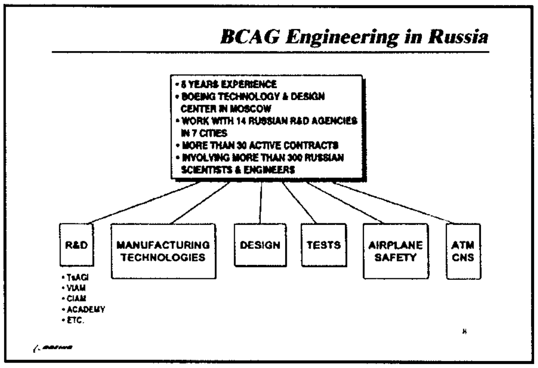
BOEING INTERNATIONAL COOPERATIVE PROGRAMS



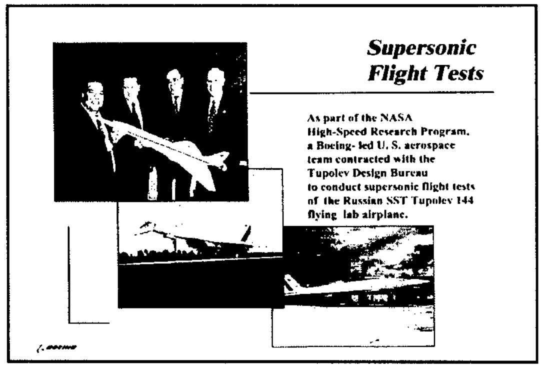






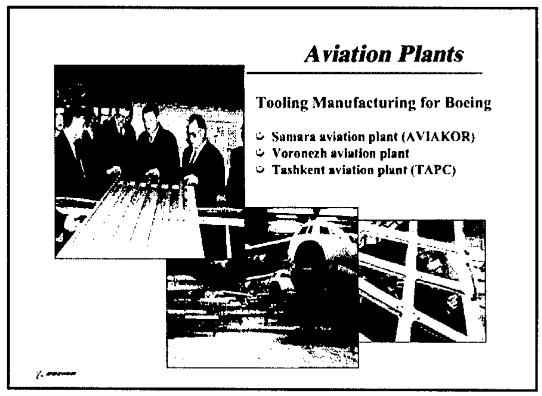


BCAG Engineering in Russia
• 5 YEARS EXPERIENCE
• BOEING TECHNOLOGY & DESIGN CENTER IN MOSCOW
• WORK WITH 14 RUSSIAN R&D AGENCIES IN 7 CITIES
• MORE THAN 30 ACTIVE CONTRACTS
• INVOLVING MORE THAN 300 RUSSIAN SCIENTISTS & ENGINEERS
R&D
MANUFACTURING TECHNOLOGIES
DESIGN
TESTS
AIRPLANE SAFETY
ATM CNS
• TsAGI
• VIAM
• CIAM
• ACADEMY
• ETC.

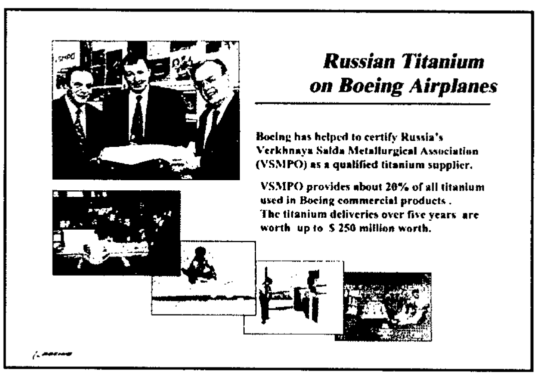


Supersonic Flight Tests
As part of the NASA High-Speed Research Program, a Boeing- led U. S. aerospace team contracted with the Tupolev Design Bureau to conduct supersonic flight tests of the Russian SST Tupolev 144 flying lab airplane.

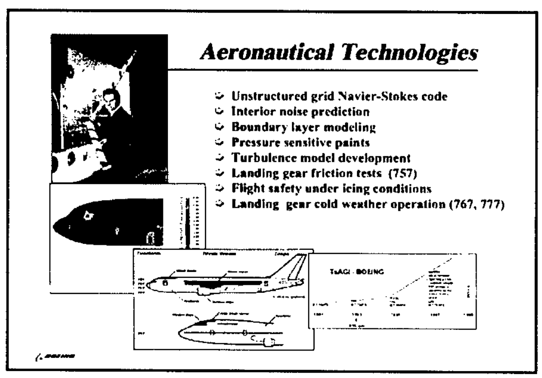
Joint Design
In 1998 Boeing and the Ilyushin Design Bureau launched the first joint redesign project, i.e. the redesign of the 777 center beam arch.
The project blazed the trail for a number of joint design works and an expansion of the Boeing Moscow Design Center.



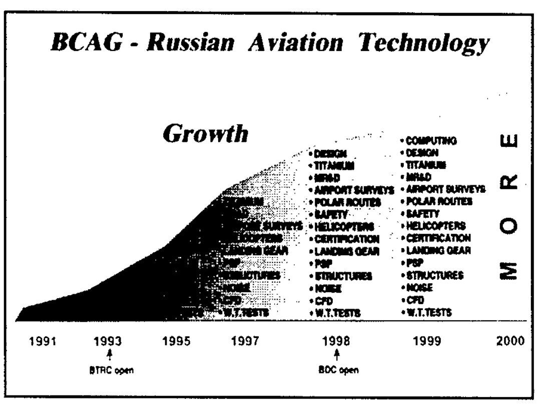
Aviation Plants
Tooling Manufacturing for Boeing
Samara aviation plant (AVIAKOR)
Voronezh aviation plant
Tashkent aviation plant (TAPC)



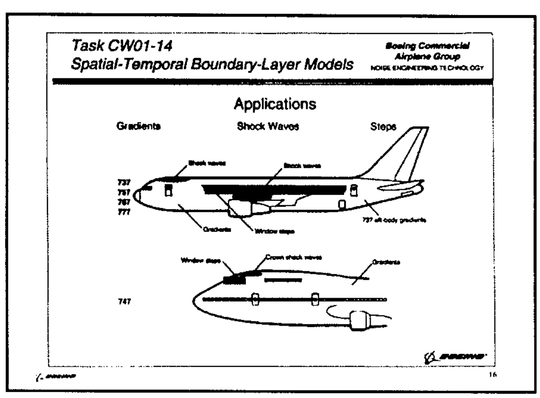
Russian Titanium on Boeing Airplanes
Boeing has helped to certify Russia's Verkhnaya Salda Metallurgical Association (VSMPO) as a qualified titanium supplier.
VSMPO provides about 20% of all titanium used in Boeing commercial products .
The titanium deliveries over five years are worth up to $ 250 million worth.



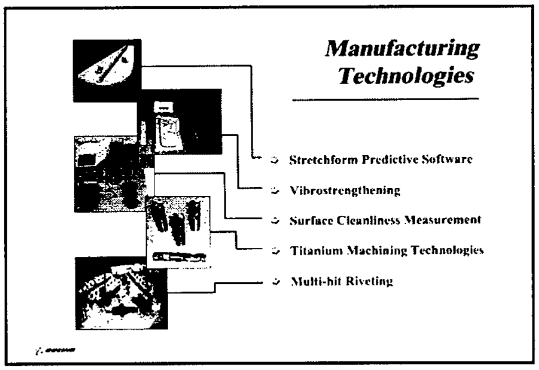
Aeronautical Technologies
Unstructured grid Navier-Stokes code
Interior noise prediction
Boundary layer modeling
Pressure sensitive paints
Turbulence model development
Landing gear friction tests (757)
Flight safety under icing conditions
Landing gear cold weather operation (767, 777)
TsAGI - BOEING

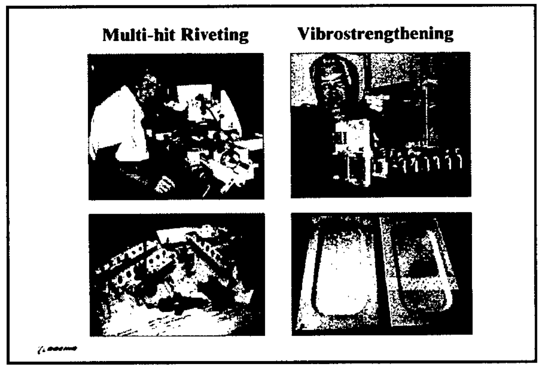


BCAG - Russian Aviation Technology
Growth
• DESIGN
• TITANIUM
• MR&D
• AIRPORT SURVEYS
• POLAR ROUTES
• SAFETY
• HELICOPTERS
• CERTIFICATION
• LANDING GEAR
• PSP
• STRUCTURES
• NOISE
• CFD
• W.T.TESTS
• COMPUTING
• DESIGN
• TITANIUM
• MR&D
• AIRPORT SURVEYS
• POLAR ROUTES
• SAFETY
• HELICOPTERS
• CERTIFICATION
• LANDING GEAR
• PSP
• STRUCTURES
• NOISE
• CFD
• W.T.TESTS
MORE
1991
1993
BTRC open
1995
1997
1998
BDC open
1999
2000

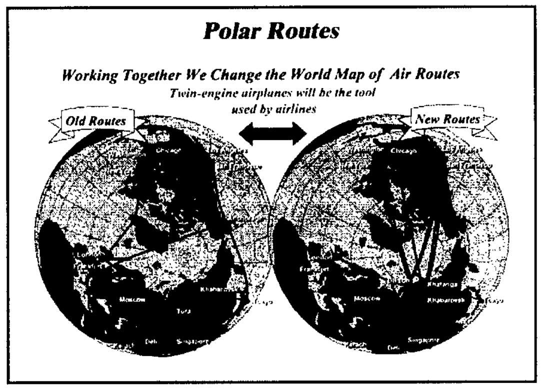


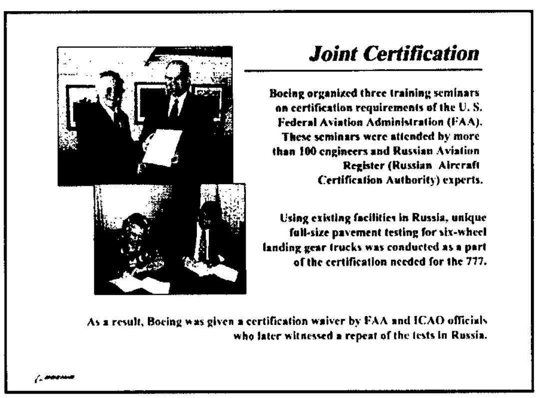
Task CW01-14
Spatial-Temporal Boundary-Layer Models
Boeing Commercial Airplane Group
NOISE ENGINEERING TECHNOLOGY
Applications
Gradients
Shock Waves
Steps
737
757
767
777
747
16

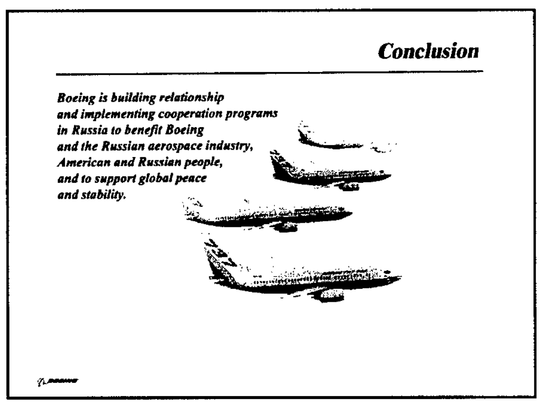

Manufacturing
Technologies
Stretchform Predictive Software
Vibrostrengthening
Surface Cleanliness Measurement
Titanium Machining Technologies
Multi-hit Riveting


Multi-hit Riveting
Vibrostrengthening


BCAG Flight Safety Programs in Russia
Airplane Safety
Accident Prevention Program
Aging Fleet Worldwide
Simple Universal ATM Worldwide
Working Together
MANUFACTURERS
• Boeing
• Airbus
• SAAB
• TUPOLEV
• ILYUSHIN
AIRLINES - OPERATORS WORLDWIDE
• USA
• EUROPE
• CHINA
• RUSSIA/CIS
INTERNATIONAL & REGIONAL CERTIFICATION AGENCIES
• ICAO
• FAA
• RUSSIAN AVIATION REGISTER
• FLIGHT SAFETY FOUNDATION


Polar Routes
Working Together We Change the World Map of Air Routes
Twin-engine airplanes will be the tool
used by airlines
Old Routes
New Routes


Joint Certification
Boeing organized three training seminars on certification requirements of the U. S. Federal Aviation Administration (FAA). These seminars were attended by more than 100 engineers and Russian Aviation Register (Russian Aircraft Certification Authority) experts.
Using existing facilities in Russia, unique full-size pavement testing for six-wheel landing gear trucks was conducted as a part of the certification needed for the 777.
As a result, Boeing was given a certification waiver by FAA and ICAO officials who later witnessed a repeat of the tests in Russia.


Conclusion
Boeing is building relationship
and implementing cooperation programs
in Russia to benefit Boeing
and the Russian aerospace industry,
American and Russian people,
and to support global peace
and stability.


10

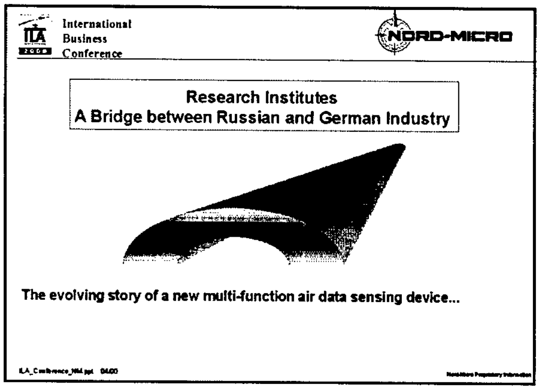
Thomas LIEBERT

Born 1958 in Frankfurt/Main Germany

Graduated in 1984 from Technical University Darmstadt, Masters Degree for Mechanical Engineering.

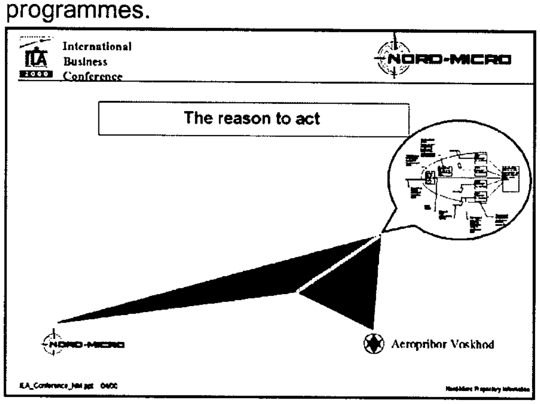
Joined Nord-Micro as a Software Design Engineer for Flight Control Systems in 1984. Moved to Marketing and Sales organisation in 1988, Sales Engineer for Military Products until 1998, now Manager R & D Marketing and Contracts.

RESEARCH INSTITUTES – A BRIDGE BETWEEN RUSSIAN AND GERMAN INDUSTRY



Research Institutes – a Bridge between Russian and German Industry

A question – or an opportunity. We will not find the answer here and today, However, I will speak to this audience about a project, which successfully started when the traffic lights were green to walk, which ran into temporary problems but came to a successful conclusion. Lessons learnt from our project can be used for future bridge building programmes.



What was the reason to act?

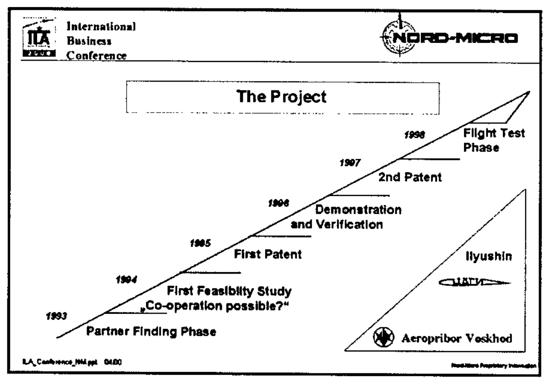
In the beginning of the nineties Russian and German aerospace enterprises were looking for capable partners to enhance their position in evolving new markets.

The baseline situation was that typically the German company was a specialist for its products in the Western market and the Russian company was the specialist in the Eastern market. For a long time and with substantial success.

Nord-Micro from Frankfurt/Germany is a German Supplier for Air Data Systems and Pressure Sensors. Aeropribor Voskhod from Moscow/Russia is a Russian Supplier for Air Data Systems, Air Data Probes and Pressure Sensors.

But: New technology must still be developed and market penetration is difficult for many reasons.

So it was logical to combine skills and knowledge of the two markets. A vision for a new product is existing. State-of-the art technology may be adopted to fit for an application in the global market.



The Project

A first study was made in order to determine whether a co-operation could lead to a feasible partnership in future international air data programmes.

Aeropribor Voskhod enlisted the support of the Central Aerohydrodynamic Institute Zhukovsky.

A first patent for a multifunction air data probe was developed and filed.

Although the project went along with some problems the partners were encouraged to continue their co-operation with a second study.

TsAGI became more directly involved and logically became a subcontractor and later on a full partner.

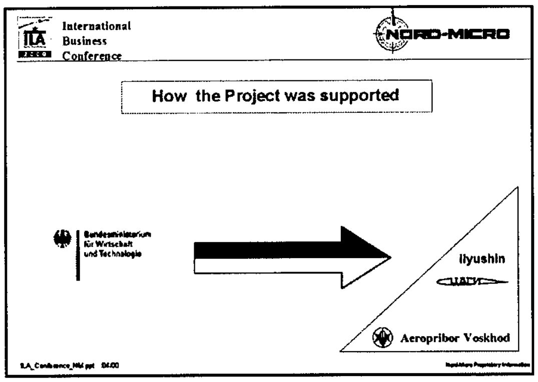
A second patent was developed and filed under the scientific lead of TsAGI with contributions of Aeropribor Voskhod and Nord-Micro.

The newly developed multi-function air data probe was successfully flight tested with the help of Ilyushin on a Il-76.

Contractual agreements were put in place for the industrial exploitation of the anticipated product.

The results anticipated for the end of the feasibility phase were planned to be the basis for the marketing of a future product.

However, the qualification of the multi-function probe against western standards could not be achieved due to different western certification standards. Needless to say that certification is essential prior to any commercial marketing in the western aerospace market.



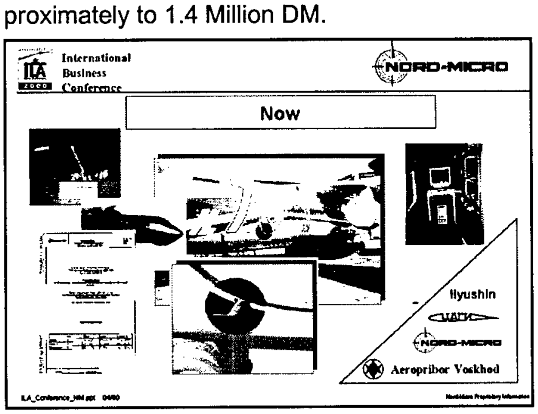
How the Projected was supported

The German Federal Ministry of Economics and Technology BMWi co-funded the research project from 1994 until 1998.

The TsAGI research institute contributed substantial scientific competence and long term international industrial experience. The contribution involved not only scientific work but also project management skills for the Russian side.

Ilyushin was added to the team as a valuable subcontractor for carrying out the flight tests on an Ilyushin 76 aircraft.

Between 1994 and 1998 the funding contributed by the BMWi amounted to 1.2 Million DM. The share self financed by the Parties was approximately to 1.4 Million DM.



Now:

Distinctive goals had been set in the programme. This is the outcome:

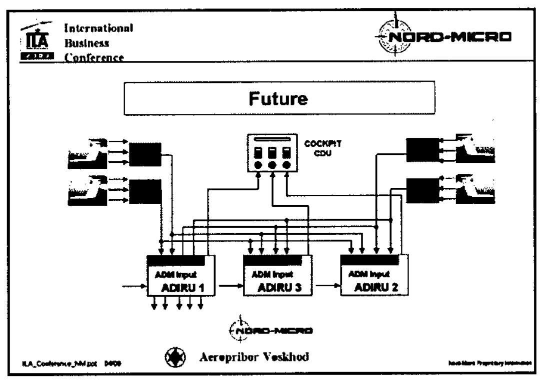
The latest feasibility study about the marketing potential of a new multi-function air data probe has come to the following conclusion:

The principal functionality of the new multi-function air data probe has been demonstrated in flight tests with the Il-76.

The market situation is changing compared to the forecasted "visions". The western market in general is still at a high peak, the eastern market is struggling with economic problems.

The western aircraft manufacturers are changing their purchasing policies, so that only larger packages from fewer supplier will be bought. This means that a probe will also be part of a larger package.

The chance to introduce a multi-function probe through the Russian market is currently quite low. Suppliers to the eastern market have to face a reduction of their industrial involvement due to the decreasing civil and military aviation market in Russia. The anticipated industrial evolution was slowed down followed by a lack of improvements i.e. a migration to western quality management standards and with respect to the establishing of economical structures of their companies.



Future:

Although research institutes are sensitive towards the industrial barometer as well, they have been and are still able to boost industrial co-operation with their skills, management capabilities and infrastructure.

The industrial exploitation of the multifunction probe is not achievable through the originally conceived concept. Demonstration of a functioning product can only be achieved through a viable Russian aircraft programme.

More funding will have to be made available to use the research institute's capabilities for the exploitation of technology in favour of industrial products. Initiatives to raise more national or European funding have not been successful so far.

And now a final statement to the bridge building business:

The step to introduce TsAGI directly as a project partner was of substantial importance to the success of the programme.

It should serve as a positive example for future industrial co-operations.

Rudolf BANNASCH

born 1952 in Berlin

1971-76 Study: Animal and Human Physiology (in the former USSR)
Diploma in Neurophysiology

1976-90 Biologist in the Institute of Vertebrate Research, Academy of Sciences
- functional morphology of the flight apparatus in birds (skeleton, joints, muscles, neuronal control), studies on aerodynamics, modelling
- several Arctic and Antarctic expeditions
- PhD on the «Underwater flight» of penguins (morphology, kinematics, hydrodynamics, energetics)
- comparative studies on swimming and flying animals

1990-98 Department of Bionics and Evolution Technique, Technical University of Berlin
- bionic research and practical applications in engineering (aero- and hydrodynamics, design of low-drag fuselages, bionic wing construction, robotics)

April 1999 Foundation of a bionic company "EvoLogics" (working in close contact with the Bionic Department of the TU Berlin)

Current projects: bionic airship, autonomous underwater vehicles, biological inspired propulsion systems, underwater communication, bio-robots with artificial (fluidic) muscles, flying micro-machines.

INNOVATIVE FUSELAGE, WING AND PROPELLER CONSTRUCTIONS DERIVED FROM BIONIC RESEARCH ON BIRD FLIGHT

This paper gives an overview on recent research and some of the developments made in the Institute of Bionics at the Technical University Berlin. With regard to aircraft design, the results on body drag reduction by shape optimization, new structures and concepts for bionic airfoil-constructions with self activated flaps (artificial bird feathers) facilitating separation control and multiple winglets or close looped wing-tip configurations designed to minimize the induced drag, as well as the new bionic propeller concept might be of particular interest.

1. Introduction

Bionics means the use of results of biological evolution in engineering. The breakthrough to dynamic manned flight resulted purely from a bionic approach. Studies on the flight apparatus of birds enabled Otto Lilienthal to discover and the principle of aerodynamic lift generation and to utilize it in engineering. Soon after the success of the first man-made gliders, Gustav Wei?kopf and the Wright brothers managed the motor-flight, and aerodynamic engineering started its own powerful career. However, from time to time it may be useful to come back to biology again. The bionics engineer knows that evolution optimizes ingeniously. And, in the complex flight optimization, nature had to solve a variety of problems relevant to modern aircraft design as well. Contrary to engineering, nature had a huge experimental ground. Over millions of years, a wealth of designs have been created, tested and optimized. The sometimes spectacular achievements of animal locomotion clearly indicate that, in view of the fluid-dynamic refinements, engineers can still learn from nature.

Indeed, a comparison of the costs of transport of animal flight with that of aircrafts and helicopter in a dimensionless way shows that nature has found much more economic solutions [1]. But animals fly at quite low Reynolds numbers ranging from just under 200 for small insects to less than 106 for the fastest large birds. Scaling rules predict that they may not deal with the same flow and drag problems as does engineering. In the aquatic environment, however, at least the fastest swimmers may encounter flow regimes comparable to those of technical bodies (e.g. subsonic aircraft, small ships and submarines). But, due to the enormous diversity in life styles, feeding and survival strategies, principles of force generation and the many other functions incorporated in the animal's body, many details and structural solutions to the problem of bio-propulsion and natural drag reduction still remain undiscovered or ill-understood. It makes little sense, and in many cases, it is virtually impossible to copy the structural solutions developed by nature. However, especially in fluid-dynamics, the bionic approach can provide a lot of inspiration. The aim is to single out the mechanisms governing biological adaptation, to understand the general "idea", the direction of optimisation and to have a further look at how to transfer these principles or how to extend these developments into the dimensions and materials applicable in engineering. Nature's method of optimisation is a further domain of the bionics engineer. By means of the Evolution Strategy [2] optimal configurations for a new parameter constellation can be found and, sometimes, it can help also to prepare a breakthrough into completely innovative concepts.

2. Low Drag Bodies from Nature

No doubt, amongst a large variety of other refinements, shape optimization represents the basic and most important measure for fluid-dynamic drag reduction. First of all, streamlining has to ensure that the flow does not separate from the

body surface, that is to keep the pressure drag low. Further adjustments are required to achieve favorable flow conditions in the boundary layer in order to reduce the wall shear stress, what means friction drag. Eventually, additional mechanisms (like polymer ejection, drag reducing surfaces etc.) may be applied, possibly in conjunction with some special adaptations in the body shape, to facilitate further drag reduction.

As early as 1800 Cayley (cited in [3]) had proposed to take the shape of the trout as an model for the (future) design of aircraft fuselages. About one hundred years later, streamlining led, indeed, to fish-like designs, for example in the Parseval-17 airship. For such huge constructions, the prevention of flow separation represented the most important consideration.

In the sixties, Hertel [3, 4] concluded that the body geometry of trout, tuna, sharks, dolphins and blue whale, in comparison to technical profiles, represent "laminar-flow spindles". He used this as an argument to replace the "transport tubes" of commercial aircraft by laminar fuselages since the latter offer the largest volume for the lowest drag. Hertel showed that the existing engineering knowledge can help to estimate natural shapes, but his experiments were not designed to study the phenomena of biological shape optimization in natural objects.

In fact, our knowledge about the boundary layer development in fast swimming animals is rather poor. For the most part, conclusions have been made solely on the base of technical analogies.

Experimental studies of the fluid dynamic properties of live swimming or flying animals are crucial. Their flexible bodies are adaptable to particular flow conditions. In fish and dolphins the body is strongly involved in the process of thrust generation, and is thus exposed to highly unsteady effects which can hardly be reproduced experimentally. For the most part, studies with rigid models have been rather disappointing, and various numerical approaches to discover the secrets of the dolphin swimming, namely to solve Gray's Paradox [5], led to controversial results. Some authors [6, 7] reject the existence of any drag reducing mechanisms in dolphins, but concluded that these animals are more powerful than assumed before. Others [8] contend that the hydrodynamic efficiency of the fluke has been largely overestimated. After respective correction it turned out that, Gray could have been right. Indeed, these animals must be able to use special methods for drag reduction. Apart from the ability to delay considerably the laminar-turbulent transition in the boundary layer by compliant wall effects [9 – 14] possibly in conjunction with polymer secretion from the eye [15] to keep the turbulence at a low level, drag reduction was referred by Romaneko [8] mainly to favorable pressure gradients actively generated by the wave-like body motion. He had conducted first measurements on the pressure fluctuation and wall shear stress on live animals.

In the framework of an European research project (INTAS 94-3737), we tried to combine our effort in bionic research with that of other research partners in the UK and Russia. Thereby we have been engaged also in the study of compliant coatings. The group of P. Carpenter, University of Warwick demonstrated that in theory, at least, substantial transition delays are possible with compliant coatings. In their experiments using a compliant rotating disc, a stabilizing effect on the Type I inviscid instability was obtained, while an increased compliance of the wall coating is required to achieve a stabilization of the Type II viscous stability, as well [10, 11]. My own experimental work [unpublished], using a compliant coating on a penguin-like body of rotation was not conclusive, so far, possibly for the same reason. In Novosibirsk, however, B. Semenov and his group came up with some promising results in view of drag reduction achieved by complaint coatings in turbulent boundary layer flows. K.S. Choi managed to conduct some validation experiments in University of Nottingham [12, 13]. For one of the coatings, a drag reduction of up to 7% within the entire speed range of the tests was obtained. In detail, it could be shown that the intensities of skin-friction and wall-pressure fluctuations measured immediately downstream from the compliant coating showed reduction in the intensities of up to 7% and 19%, respectively. The turbulence intensity decreased by up to 5% across almost the entire boundary layer, and the thickness of the viscous sublayer increased. So, some insights into the mechanisms of turbulent drag reduction could be obtained. As claimed by Babenko [14] and others, multiple compliant panels and anisotropic coatings may offer a big potential for further optimization. On my personal view, those effects may not be restricted to hydrodynamic applications, only. Considering the highly compliant plumage covering the body of birds, nature offers a much wider field for investigation with the possibility to apply aerodynamic methods, as well. And, nature shows that there are good chances to eventually make use of those effects also for the improvement of our aerodynamic constructions.

In general, the laminar hypothesis might be not applicable to all marine animals. Sharks seems to have developed another mechanism for drag reduction. Their skin was found to reduce turbulent wall shear stress by its "riblet" structure [16 – 19].

Earlier results of Russian scientists summarized by Aleyev [19] and recently reconsidered by Videler [1] point to a further interesting mechanism of drag reduction used in nature. In swordfish, the rostrum forms a long and slender pre-body (blade), which was found both to reduce the dynamic pressure peak at the frontal part of the main body and to smooth the pressure distribution further downstream. It may also reduce the wall shear stress by increasing the local Reynolds numbers downstream. But most in-

teresting, due to its rough surface, it is likely to stimulate an early transition from laminar to "micro-turbulent" turbulent flow. Videler has designed a nice fuselage construction implementing this principle in order to improver the aerodynamic performance of the airplanes built by the FOKKER company at that time. His conclusion, however, that the boundary layer can be kept in that state by the following concave-convex shape of the head, and the theoretical assumption that such a "micro-turbulent boundary layer" may behave like a laminar one, clearly require experimental confirmation. Nevertheless – apart from sharks – the swordfish gives another example for the early development of a turbulent boundary layer in marine animals. Moreover, it represents a first indication of turbulence management by a multiply curved body profile in nature.

The Penguin Phenomenon:

As examples of shape optimization for fluid-dynamic purposes, penguins are a particularly interesting group of animals. Derived from highly evolved flying birds, they changed to aquatic life and became the best adapted birds to wing-propelled diving and swimming. After several studies conducted on different penguin species in zoos had pointed to excellent hydrodynamic properties [20–22], a comprehensive approach to the marine ecology, energetics, swimming and diving perfor-mances of penguins was developed in the framework of the German Antarctic Expeditions [23 – 30].

Telemetry showed that medium sized penguins (body length 0,65÷0,70 m in the swimming posture) can swim more than 100 km per day and dive to maximum depths of ca. 450 m. Their preferred travel speed ranges from 2 to 3 m/s, and the maximum speed is about 4,5 m/s. The larger Emperor penguins are somewhat faster, and can reach a maximum speed above 7 m/s.

Field metabolic studies supplied evidence for low energy consumption in under-water locomotion. Assuming the energy content of krill to be 3700 kJ/kg, 1 kg of that food would allow for example a 4 kg Adelie penguin to travel up to 200 km. One may try to illustrate this result in technical terms: if this penguin would be able to utilize benzine (46700 kJ/kg) instead of krill, 1 l of this fuel would suffice for a ca. 2500 km long trip in the cold ice sea!

These data point to high mechanical efficiency of the propulsion system and to particularly high achievements in body drag reduction, since the biochemistry of the flight muscles does not differ from that of other birds. Unlike in fish and dolphins, the penguin's trunk does not contribute to thrust production; trunk oscillations during a wing beat cycle are moderate. Therefore, the spindle-like penguin trunk may well serve as live example for how energy may be saved by shape optimization of stiff bodies. Our aim was to study this experimentally.

For a complex of morpho-functional studies including also hydrodynamic investigations, ten individuals were collected from each of the three pygoscelid species: Gentoo (Pygoscelis papua), Adelie (P. adeliae) and Chinstrap penguin (P. antarctica). After measuring body mass, body length, maximum girth, that individual of each species which was closest to the mean values was mounted in swimming posture and frozen. Then, models in glass fiber reinforced plastic were made [26].

The body shapes of the three species resemble one another in being spindles with high values of maximum thickness position and thickness ratio (see Table 1). A small degree of dorso-ventral asymmetry was evident from the lateral view. At the position of maximum thickness, the cross section was almost circular. Overall, the geometry of the penguin bodies would characterize them as laminar-flow spindles (sensu Hertel [3, 4]). However, the structure of the beak and a certain roughness at the beginning of the plumage suggests that the transition from laminar to turbulent boundary layer may be triggered in the very frontal part of the body, and moreover the "wave-like" outlines of the forebody look somewhat unusual.

Based on the arithmetic means of the respective diameters at 70 points along the axis, an axisymmetric body of revolution (Table 1, Fig. 1) was turned on a lathe.

Table 1

Geometry of penguin bodies. A frontal area [m²], d diameter of the frontal area [m], ℓ body length [m], x_d abscissa of the maximum thickness [m], ℓ/d length to thickness ratio, x_d/ℓ maximum thickness position.

Species	ℓ/d	x_d/ℓ	A	$d = \sqrt{4A/\pi}$
P. antarctica	4,54	0,44	0,01959	0,158
P. adeliae	4,35	0,47	0,02083	0,163
P. papua	4,00	0,44	0,02706	0,186

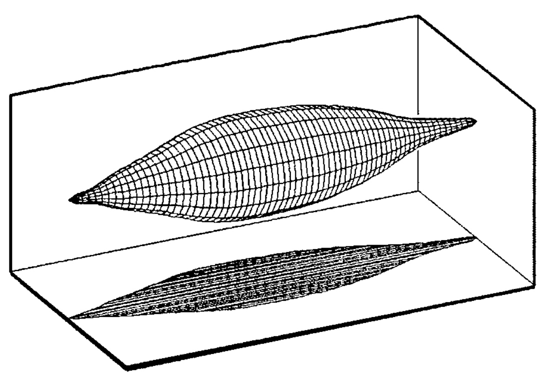


Fig. 1. Body of rotation derived from penguin data

Flow Visualisation and Drag Measurements:

Visualisation experiments in a smoke-wind tunnel showed a smooth flow around the penguin body. Even at a free stream velocity of 11 m/s (which corresponds to 0,7 m/s in Antarctic seawater) separation occurred only in the tail region.

Some increase of the velocity caused a downstream shift of the point of detachment and thereby a reduction in the diameter of the wake. It can be predicted, that at the normal travel speed of penguins (ca. 2÷2,5 m/s) flow separation at the body surface does not occur at all.

In order to cover the range of Reynolds numbers used by the respective penguin species in their natural environment, drag measurements were conducted in the large circulating tank of the Versuchsanstalt fur Wasserbau und Schiffbau (VWS; the Berlin Model Basin). In the test section (8 m long and 5 m wide) wall effects were excluded. The water depth was adjusted to 1.5 m by elevation of the floor. The turbulence in the circulating tank was relatively high. The turbulence factor was 1.8÷2.0 (determined by means of the critical Reynolds number of an ideal sphere). The penguin models were fixed to steel bars (length 1 m, diameter 15 mm) placed in the long axis of the body. The end of the bar was attached to a vertical rod encapsulated by a low drag cowling, and the rod was attached to a balance. The models were submerged to a depth of 75 cm. This was much deeper than 3 times the vertical height of the body in a swimming position, which is a depth below which drag augmentation by surface effects is negligible [3].

Fig. 2 shows the frontal drag coefficients c_{Df} of the penguin models plotted against Reynolds numbers Re_0 (using the diameter d as reference length). All three models showed a very similar characteristic best approximated by a logarithmic function: $c_{Df} = 11.975 \times Re_d^{-0.4434}$ (correlation coefficient $R = -0{,}943$, $p = 0{,}001$).

At lower Re, the results coincided with those of other authors [21], but the best values ($c_{Df} = 0{,}03$) obtained from the Adelie and Gentoo models at $Re_{d'max}$ (flow velocity 4,5 m/s) were surprisingly low.

The body of revolution showed an opposite tendency. Starting from already very low values (under 0,02!), the c_{Df} declined first to 0,0156 (at $Re_d = 2{,}331 \times 10^5$). Thereafter it increased to finally 0.03 and then decreased again following the regression line of the original penguin models. This was clearly an effect of transition from laminar to turbulent flow in the boundary layer. To prove this experimentally, a 1 mm thick wire ring was attached to the nose of the body in order to trigger the transition at 5% of the body length. Thereafter, the body of revolution showed nearly the same characteristics observed in the penguin models (Fig. 2). From this similarity, we concluded that the boundary layer in our penguin models must also have been turbulent. At this stage, we could not answer the question about applicability to live animals, but the axisymmetric penguin-like body seemed to offer promising perspectives for technical applications.

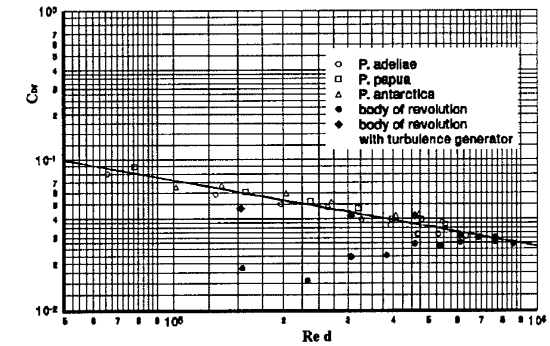


Fig. 2. Frontal drag coefficients plotted against Reynolds numbers. In this graph, Re was calculated by using the maximum diameter d as reference length

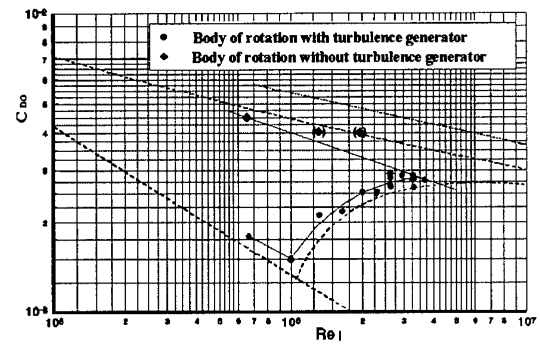


Fig. 3. Surface drag coefficients of the body of rotation plotted against Reynolds numbers. Note that in this graph Re was calculated by using the body length l as reference length. The two values in brackets should be neglected (artificial drag increase due to unfavourable Froude numbers in the test section). Dotted lines: laminar (below) and turbulent (above) flat plate. Dashed line on top: turbulent bodies with a length to thickness ratio of 4.2, cf. [31]

To compare the results obtained from the body of rotation to those reported by Hoerner [31], the surface drag coefficients cDO were plotted against Reynolds numbers using the body length l as characteristic length (Fig. 3). Most surprising, in the turbulent case the surface drag coefficients of our axisymmetric body remained even lower than those of a turbulent flat plate of equal length, and with increasing Reynolds numbers they declined at a higher rate. Drag coefficients were some 30÷35% lower than those reported for the best turbulent technical bodies [31].

Pressure and Velocity Distribution Along the Contour of the Axisymmetric Penguin-Body:

Together with students of the Institut fur Luft- und Raumfahrttechnik der TU Berlin, another (hollow) model of the body of rotation was built and equipped with pressure holes. We had to cut off the tail of the body to facilitate connection of the tubes glued inside the holes to a pressure transducer (via a scanivalve) outside of the test section. The pressure distribution was determined in a wind tunnel at various flow velocities. Additional comparative measurements were carried out on

both bodies of rotation with an external static pressure sonde (diameter: 1 mm),

Fig. 4 shows the distribution of the dimensionless pressure coefficients cP obtained experimentally by both methods in comparison with potential flow calculations (panel method without consideration of the displacement thickness).

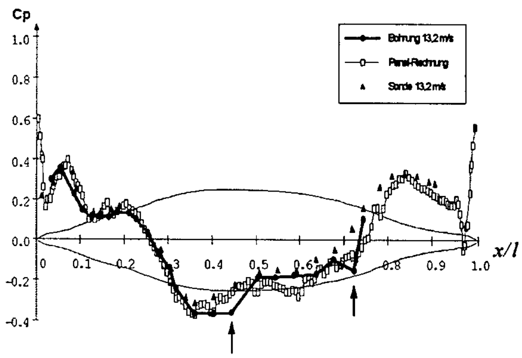


Fig. 4. Pressure distribution, experimental and numerical data

Apart from small deviations at the points indicated by arrows (probably two defective pressure holes), the results coincide well for the frontal part of the body. At the rear, the differences became somewhat larger since each method implied certain disadvantages. The general tendency, however, was similar in all three approaches.

Contrary to conventional bodies, where the pressure continuously decreases towards and increases beyond the maximum girth position, a more stepwise pressure distribution was found in the present case,. Most remarkable were the roughly similar gradients (slopes) along the forehead, the beginning of the trunk, and – with the opposite sign – also at the end of the trunk. Consequently over the convex areas, the flow was accelerated or decelerated at a nearly constant rate, respectively. Over the intervening slender (concave) parts, the pressure – and consequently also the flow velocity – remained nearly constant (plateau). This unusual pressure fluctuation can be described by a secondary wave superimposed on the main curve. The wave length increased in correspondence with the local Reynolds number. It should be noted, however, that at the beak, the depression in the pressure distribution changed to a plateau when the transition from laminar to turbulent flow was triggered at that point by a wire ring. The downstream pressure distribution was not altered by this measure.

The relatively good coincidence of the experimental results with those obtained from potential flow calculations indicates a low pressure drag. The total drag of the given body seems to be mostly due to friction.

Paint flow Visualisation:

To get some insight into the development of the near wall flow pattern, the paint flow method was used. The body of rotation was evenly painted with a mixture of petroleum, oil acid and titanium white and exposed then to an air stream of 20 m/s ($Re_\ell = 9.3\times10^5$). This was the maximum speed allowed by the free steam wind tunnel of our department. After evaporation of the oil, the remaining titanium gave an impression of the flow pattern at the surface of that multiple curved body. Fig. 5 shows the result from two different experiments (without and with turbulence generator at the base of the beak).

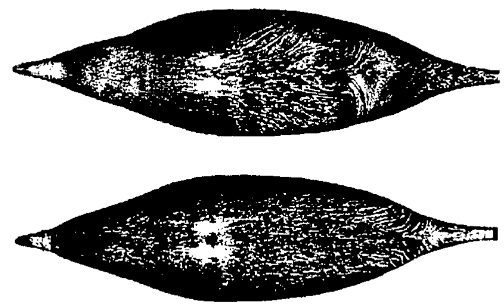


Fig. 5. Paint-flow visualisation on the body of rotation without (above) and with turbulence generator (below). Top view in both cases

In the picture without turbulence generator (Fig. 5 above), three main zones can be distinguished. In the frontal part (up to ca. 40% of the body length), the flow was stepwise accelerated and remained laminar. The tiny structure of the pigments indicates a relatively high wall shear stress.

Friction was highest over the convex parts (tip of the beak, forehead, frontal part of the trunk). However, some relaxation of the boundary layer (increase of the structures imprinted) could be observed along the concave parts at the origin of the beak and in the neck region. The second zone reaches from ca. 40 to 70% of the body length. Here, the flow seemed to be still laminar, but the structures imprinted grew very fast. The diverging paint flow lines indicate a considerable relaxation of the boundary layer. Especially at the sides of the body, the pigments were driven in an oblique direction since gravity started to dominate over the friction forces. Finally, with a sharp border, a (probably) laminar detachment zone with turbulent reattachment at the tail was formed.

Possibly in the present visualisation experiment, the wind velocity was too low to keep the flow fully attached. It was also possible that the rear of the body was not optimally shaped. When constructing the axisymmetric body, we did not know how to deal with the feet. Finally, that part was smoothed by hand. The design was, however, not that bad. At the tail, the flow reattached, and a drag penalty due to an unbalanced pressure distribution could be avoided. Otherwise the extremely low drag coefficients (C_{DO} = 0.018) measured at similar Reynolds numbers in the water tank could hardly be explained.

The picture changed completely when the turbulence generator (wire ring) was placed at the nose of the body (Fig. 5 below). The concentration of titanium white pigments at the base of the beak marked a stationary ring vortex generated by the wire. The respective separation area had a sharp border. In the first experiment, a similar patch was formed in that area, but its margins were blurred; possibly a ring vortex or laminar detachment bubble was also formed at the end of the beak without turbulence generator. However, due to the laminar reattachment it did not influence the flow pattern downstream. But in the second case, the flow reattached turbulently. Although larger disturbances were immediately dampened out due to the flow acceleration at the following convex forehead, certain microstructures introduced into the boundary layer by the wire ring survived. The paint flow pattern increased in size continuously but rather slowly. Even at the end of the body, these structures remained much smaller than in the experiment without a turbulence generator. The influence of gravity on the direction of the paint flow was less pronounced, implying that the wall shear stress was higher. Since the boundary layer contained more energy, the detachment zone was shifted towards the tail of the body.

In general, the paint flow pattern obtained in the second experiment suggests a certain similarity with the structure of the plumage in real penguins, in which the size of the feathers increases from the head towards the end of the body at a similar rate. It might be worth noting here also that the microstructure of the penguin plumage is somewhat reminiscent of the riblet pattern known from the shark skin to reduce the turbulent wall shear stress [18].

Hot-Wire Anemometry:

Further insights into the near wall flow at the penguin-like body of rotation were gained by using hot-wire anemometry in the large (closed) wind tunnel of the Hermann-Fottinger Institut fur Thermo- und Fluiddynamik der TU Berlin. Here, we could obtain a flow velocity of 25 m/s at which the Reynolds number ($Re_\ell = 1{,}2\times10^6$) corresponded to that preferably used by the pygoscelid penguins in the Antarctic Sea (mean travel speed: 2.3 m/s in saltwater at 4°C).

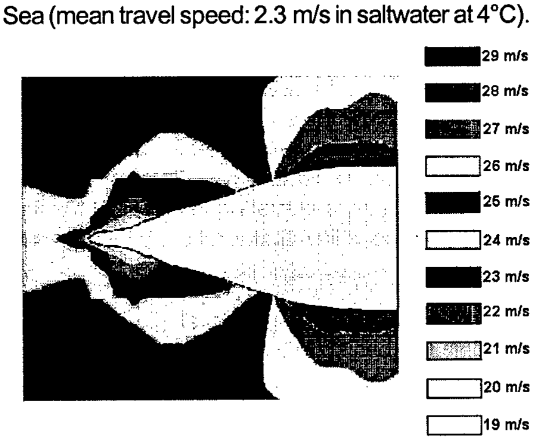


Fig. 6. Velocity distribution in the outer flow around the frontal part of the axisymmetric penguin body

Owing to the limited experimental time provided, detailed investigations could be conducted only on the flow around the wave-like frontal part of the body. Fig. 6 shows the velocity distribution in the outer flow field.

In this picture, the stagnation point was not well marked. It lay close to the tip of the beak. Generally, the influence of the body on the flow field in front remained moderate. A zone of decelerated flow was vertically extended over the concave part of the beak. Following a short acceleration over the convex forehead, the flow velocity near the wall remained nearly constant at the neck. This corresponds to the first pressure plateau in Fig. 6. At about 26% of the body length, the free stream velocity was reached (no variation with distance from the body surface). This was the point where the pressure curve crossed the abscissa (Fig. 4). Downstream, a zone of hypervelocity was developed, with as expected, centre at the thickest part of the body.

The effect of this unusual flow pattern on the velocity profiles within the boundary layer is shown in Fig. 7. Most remarkable in both experiments (without and with turbulence generator) was that the thickness of the boundary layer increased suddenly at the base of the beak and thereafter remained nearly constant. In the laminar case, the S-shaped velocity profiles C-F might suggest the flow was close to separating. That would point to extremely low friction in this area.

It was evident from the doubly curved profile C that a shallow separation bubble was formed at the base of the beak (see discussion of the paint flow experiment).

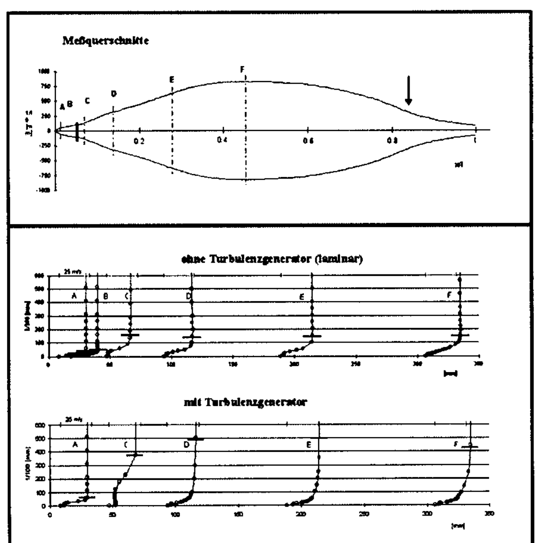


Fig. 7. Velocity profiles in the boundary layer at the wavy frontal part of the body measured by hot-wire anemometry. The horizontal lines indicate the boundary layer thickness corresponding to 99% of the velocity of the outer flow. Top: position of the measuring points; middle: velocity profiles without turbulence generator; bottom: with turbulence generator

When the body was equipped with the turbulence generator, the boundary layer was about three times thicker than in the laminar case, and the velocity profiles were more rounded. The unusual shape of profile C can be explained as a registration of the wake of the wire which was, obviously, somewhat too large (diameter of the wire in this case: 2 mm). The downstream profiles were no longer S-shaped.

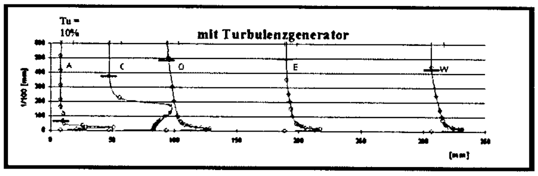


Fig. 8. Turbulence profiles. Transition was stimulated at ca. 5% of the body length. Points of measurement same as indicated in Fig. 7, with mean of the turbulent velocity fluctuation, free stream velocity, cf. [32]

The turbulence profiles shown in Fig. 8 support the ideas developed from the paint flow experiments. The huge disturbances introduced by the wire ring serving as turbulence generator (profile C) were quickly dampened out. Further downstream the turbulent velocity fluctuations were considerably reduced and were restricted to a relatively thin layer near the wall. Although the overall frequency spectrum was quite broad, at the maximum thickness position of the body a definite peak was observed at 3.1 kHz.

When an early transition was stimulated, the magnitude of the velocity fluctuation within the boundary layer was much lower at the end of the body than in the case of natural transition (Fig. 9). Although in the last experiment, the flow velocity was higher, so that the detachment zone at the end of the body was likely to disappear, the result coincided well with the pictures observed in the paint flow experiments.

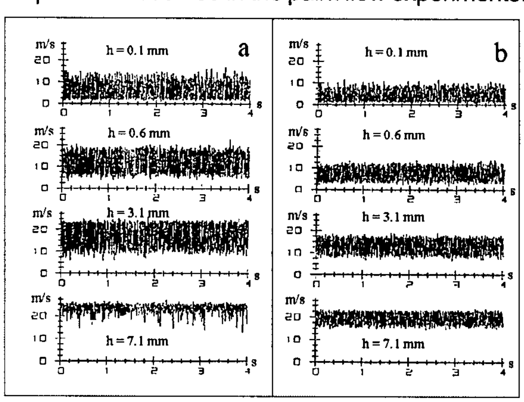


Fig. 9. Velocity fluctuations at the rear of the body (position: see arrow in Fig. 7). a (left side): without and *b* (right side) with turbulence generator; *h* distance from the body surface (from top to bottom: 0.1 mm, 0.6 mm, 3.1 mm, and 7.1 mm)

Apart from the 99% thickness, the boundary layer is characterised also by the displacement thickness δ_1 and the momentum thickness δ_2 [26]. Our investigations focused only on the frontal part of the penguin-like body of rotation, but even here remarkable differences from those of a flat plate and conventional streamlined bodies could be observed. In the axisymmetric penguin body, the development of δ_1 and δ_2 was in general analogous to that of the 99% thickness. At the end of the beak, all three boundary layer thickness parameters suddenly increased to values 1.5÷2.0 times higher than those of the flat plate at a similar distance from the leading edge. In the body of rotation, the first pressure step seemed to generate boundary layer conditions which can be found on a flat surface only at considerably higher local Reynolds numbers, and in usual (three- dimensional) bodies even later. This mechanism may contribute to a drastic reduction of the local wall shear stress. But it involves also a certain risk. At the pressure step at the end of the beak, δ_2 did not jump as much as δ_1. Consequently, the shape parameter H_{12} ($H_{12} = \delta_1/\delta_2$ showed a peak at this point. In the laminar as well as in the turbulent case, it considerably exceeded the respective values known to be crucial in view of flow detachment from a flat surface. Downstream that point, the shape parameter recovered to values slightly below the critical ones (laminar case), or became even more stable (in the turbulent case).

It should also be noted that the nose of the test body might have been less optimally shaped than the asymmetrical beak of a real penguin. It was possible that the separation bubble observed in our experiments was an artefact resulting, on the one hand, from the means of the contour coordinates being used and, on the other hand form the large diameter of the wire ring attached. So, there seems to be some potential for further optimisation of the artificial body.

Independent investigations of the wake of the axisymmetric penguin body conducted in another wind tunnel using hot-wire anemometry as well as studies on a somewhat smaller model in a circulating water tank by means of Laser-Doppler-Anemometry supported the very low drag coefficients of the given body shape.

The penguin body seems to be evolved to get use from several drag reducing mechanisms in combination. At the tip of the beak, the only way to reduce the effect of the unavoidably high friction on the total drag is to keep the diameter, and thereby the wetted surface, small. Since the transition causes a peak in the wall shear stress, it might effective to trigger the transition while the circumference is still small. The drag penalty resulting from early onset of turbulence might be moderate since, simultaneously, much stress is taken out by making the boundary layer thicker. Here, one may question the advantage of an early increase of the boundary layer thickness since the total drag equals the momentum loss at the end of the body. Unfortunately, we could not sys-

tematically study what really happened at the rear or in the wake of the penguin-like body. However, at the position of the maximum diameter, all three thickness parameters of the boundary layer were about half to two thirds of the values for a flat plate. The convex forehead serves as a kind of high-pass filter allowing only a certain micro-turbulence to survive. Keeping the boundary layer at a nearly constant thickness, then, may help to restrict the frequency band. Ideally (and hypothetically) this "tuning" mechanism may restrict the turbulent pressure and velocity fluctuations to those best controllable by the dampening properties of a compliant body surface. Although, this has to be verified experimentally; there is every indication that this mechanism plays an important role in drag reduction of life penguins.

Flow-Visualization in Life Penguins:

During our last Antarctic expeditions, special hydrodynamic studies were carried out on live penguins swimming in a 21 m long still water tank (cross section ca. 1×1 m). For this purpose, a novel method for flow visualization in live animals with controlled dye ejection from underneath of the plumage was developed. In combination with conventional video and high-speed video analyses, fundamental insights into the details of the boundary layer development in various flow conditions and into its interaction with the vortex system generated by the wings could be obtained. These visualization experiments confirmed that transition occurred in the most frontal part of the bird's body. However, the boundary layer never became „chaotic" further downstream. In most cases, a quite regular wavelike pattern (wave length 2÷3 cm with only the amplitude increasing towards the end of the body) was formed. The waves had a velocity of approx. 95% of the swimming speed, and appeared to be nearly stationary in the fluid (Fig. 10).

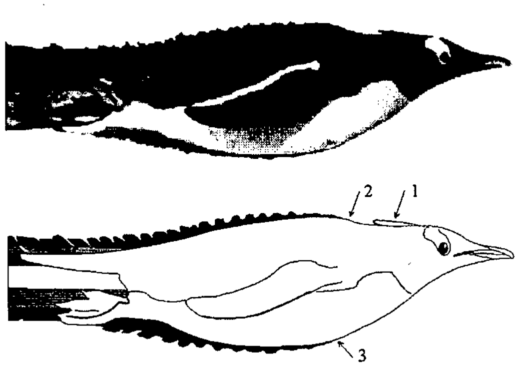


Fig. 10. Boundary layer visualisation in a live Gentoo penguin. Above: a single picture printed out from video records. Below: Scheme obtained from the entire sequence. 1 air bubble, 2 and 3 indicate the places of dye application. Note the quite regular pattern of the intermittent flow. (Bannasch)

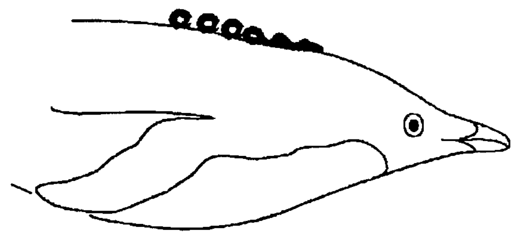


Fig. 11. Schematic graph of a rare high-speed video picture showing the development of ring structures in the boundary layer of an Adelie penguin

Apart from passive mechanisms (multiple curvature effects, compliance and microstructure of the plumage) possibly responsible for maintaining boundary layer turbulence an overall low level, the flow visualization experiments showed that the structure of the near wall flow can be managed by a number of active mechanisms. Tiny adjustments of the body shape (changes in the position of the head, neck, feet and tail) and thereby of the pressure and velocity distribution had a remarkable influence on the flow pattern.

Additionally in some cases, in the beginning of diving, some parts of the body became covered by a thin film of air that reduces the wall shear stress locally to an absolute minimum. These areas corresponded well to those characterized by a low pressure gradient in the earlier model experiments. For the most part, the air was squeezed out of the plumage. The most persistent air bubble was the one in the neck (see Fig. 10), which was frequently renewed by exhalation, and was subjected to oscillation. At this location a vortex seems to be formed which is assumed to underlie the same oscillation. This could be a possible explanation for the mechanism generating the running wave observed further downstream in the boundary layer.

Based on the pictures on the boundary layer development in life penguins, one may speculate that the early generation of coherent vortex structures might be an effective measure to stabilize the near-wall flow, and to prevent "chaotic" developments even at the end of the body. The special pressure distribution along the wavy contour of the body and the compliance of the surface of the plumage seem to be the mechanisms to control this process.

Finally, it should be mentioned that an extraordinary measure to drastically reduce body drag temporarily could be a sudden ejection of large amounts of air bubbles by the bird. Occasionally, the saturation of the boundary layer with gas bubbles can be observed when the animals try to achieve extreme acceleration e.g. during escape reactions or before jumping out of the water.

Scale Effects and Engineering Applications:

The possibility to reduce viscous drag by alternating concave-convex surfaces has been explored experimentally and theoretically in the

NASA Langley Research Centre [33-35]. Most interesting in the present context are the experiments with nose bodies. These experiments were aimed to make application of the fact that compared to a flat surface, the effect of streamwise convex curvature is to reduce skin friction, and the level remains lower even after the curvature is removed. However, the axial distribution of the cross-sectional area ratio was found to be critical to separation. A solution to this problem was found by implementing the drag reduction concept over several short fetches of curvatures instead of a single long fetch. In result, a three-stage nose body was developed (Fig. 12).

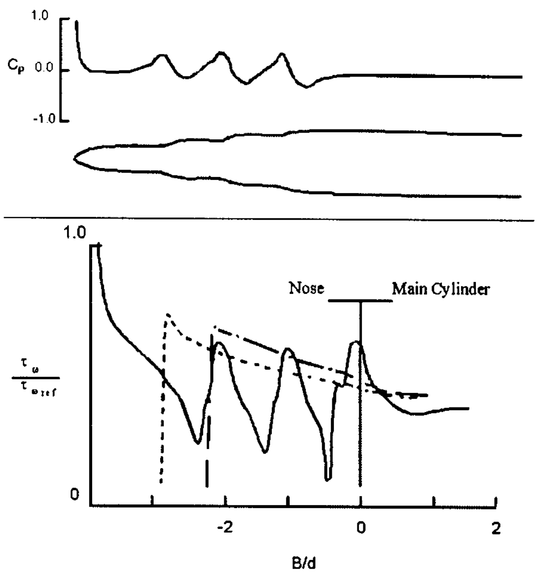


Fig. 12. Computed surface pressure distribution (above), and wall shear stress (below) in a three-stage nose body (solid line) compared with equivalent-area (dashed line) and equivalent-volume (chain line) half-elliptic noses (redrawn from [27])

Thus, the application of the convex curvature concept led to a structural solution quite similar to that developed by nature in 40 million years of evolution. The respective proportions of the three stages in the frontal part of the penguin body were, however, different from that of the three-stage nose body, and a local pressure increase was observed only at the end of the beak. But even this part of the pressure curve changed to a plateau when a turbulence generator was attached to the model. In the "natural" design, the convex parts were connected not by cylinders but by concave sections. In order to take advantage of the "memory effect" along these parts, it might be more effective to maintain the flow velocity constant instead of decelerating it before acceleration follows in the next stage. With the exception of maximum girth position, the surface flow velocity vector include always a component directed perpendicularly to the axis of the body. If maintaining this constant as well, the local cross-sectional area must change also along the intervening sections. In this way, the length to thickness ratio and thereby the surface to volume ratio of the body can be reduced. The design of respective axisymmetric bodies seems to be a good way to obtain a better understanding of wave-like curvature effects.

Recently, some numerical approaches have proved the Evolution Strategy [2] to be an appropriate method to achieve optimisation in a parallel way as used by nature. The first attempt in this direction was made by Pinebrook already in 1982 [36]. Fig. 13 shows the result of an optimisation experiment aimed to minimise the drag of a turbulent body of revolution at Re = 10^8. The transition from laminar to turbulent flow was fixed at 3% of the body length.

In Pinebrook's approach, the body contour was described by only 20 contur points equidistant with respect to the central axis. These points were varied, with the restriction that the maximum diameter and the fineness ratio were maintained. Compared to the initial shape, the body drag could be (numerically) reduced by 20÷30%, After 600 generations, a tuna-like shape, and thereafter a spindle somewhat reminiscent of the penguin shape with a well pronounced tail and a more

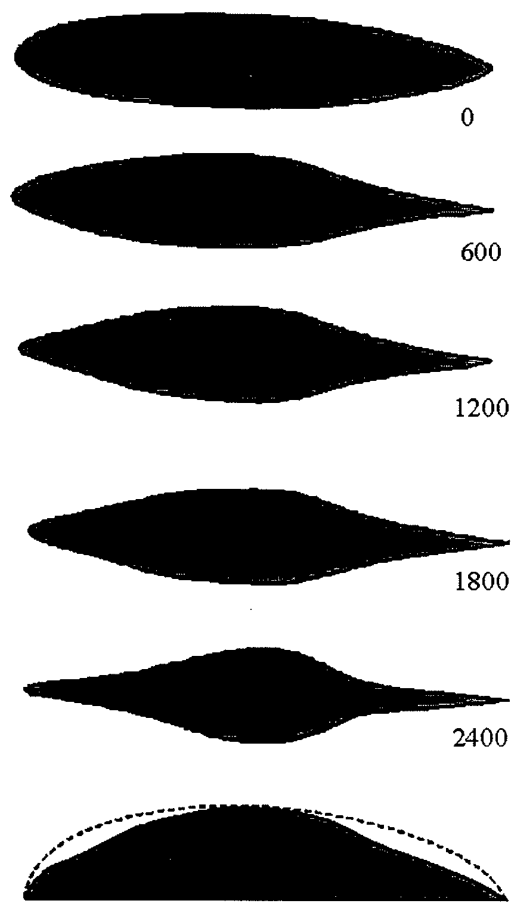


Fig. 13. Evolution of an axisymmetric body profile in the process of numerical shape optimisation (after [36]). Reynolds number 10^8; the numbers indicate the respective generation; below: profile of a thick body; dotted line: initial shape, solid line: final shape (flow direction from left to right)

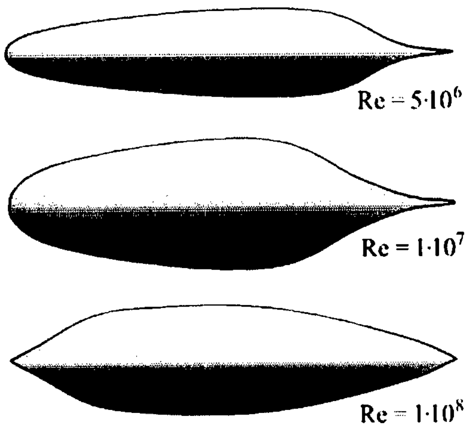


Fig. 14. Low drag bodies optimized for different Reynolds numbers by means of the Evolution Strategy (flow direction from left to right). (PhD, Th. Lutz)

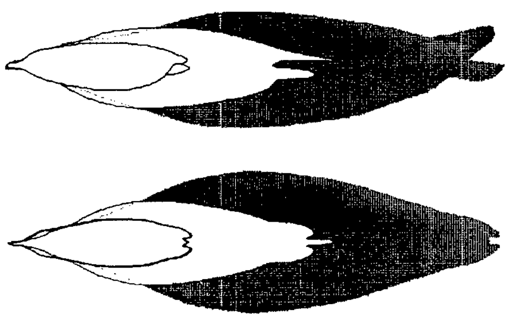


Fig. 15. Comparison of the body contours: Little, Gentoo and Emperor penguin, above: side view, below: top view

pointed nose was developed. Obviously, most of the drag reduction resulted from reduction of the body surface. In consequence, the bodies lost a considerable part of their volume.

In a new approach developed in co-operation with Th. Lutz, University of Stuttgart, those undesirable effects could be avoided. The task was to find the optimal shape for a given volume under any (given) flow conditions [37, 38]. Fig. 14 shows some results obtained from an early version of that CFD program. Meanwhile, the program could be improved further. However, based on the calculation methods implemented as yet, multiple curvature effects did simply not occur even in these simulations. In a numerical evaluation of the penguin-like body, the shape of the drag curve (see Fig. 2 and 3) could be confirmed. The curve was, however, shifted to drag coefficients ca. 20% higher than those obtained experimentally. Validation experiments are in preparation to find out whether the measurements were incorrect or the turbulence model used in the calculation was insufficient for the this particular application.

Nevertheless, since most of the higher evolved flying and swimming animals show wavy body contours, comparative studies on the curvature development with size progression seem to be promising. Fig. 15 shows a comparison of the outlines from three different sized penguin species. In these three species, the body length (in the swimming posture) changes at a ration of ca. 1 : 2 : 3, and – considering that they swim at different speeds, and the kinematic viscosity in their marine environment varies with temperature and salinity – the preferably used Reynolds numbers vary at a ratio of about 1 : 2 : 4, respectively. The Little penguin has a slender beak and a relatively big head, whereas the contour wave in the forebody of the Emperor is more extended, and its amplitude increases with length. The shape of the Gentoo seems to be an intermediate stage between these two examples. The superimposition of the contours shows that where the one curve has a maximum, the next one has a minimum, and so on. This comparison suggests that there might be some distinct ("harmonic") solutions to that kind of shape adaptation.

Considering further, that a certain dorso-ventral asymmetry is evident in the body shape of mostly all animals adapted to fast sustained swimming or flying, the understanding of the wave-like curvature concept in a three dimensional way, may eventually lead to completely new and even more "organic" designs in engineering. To find the "composition rules" (the author believes that they exists) will be particularly useful for example to better integrate cockpits etc. into the shape of the fuselage.

It has to be emphasised that the three-dimensional approach becomes essential particularly when aerodynamic lift generation becomes involved. In this case, drag reduction and lift generation must be considered in conjunction. It is not simply a superimposition of two different effects. Aircraft designer are fully aware of this problem. However, an integrated approach considering the optimisation of all parts of an aircraft together often fails because of the enormous complexity, often exceeding the limits of computation. Experimental optimisation is extremely time- and cost-intensive at that level and therefore often not applicable. But natural evolution works at all levels simultaneously. So, it might be useful to look at flying birds to find out if the various principles learned so far from penguins and axisymmetric bodies are applicable in that context as well and which modifications are required to adapt the body shape to the respective demands.

Fig. 17 shows a Giant Petrel in flight. Birds of this species belong to the large seabirds. Their flight performance compares well to that of albatrosses. Often, they fly together. Gaining energy from the velocity gradient over the surface of the sea (dynamic soaring), these birds can fly hours without a single wing stroke. Flapping flight is used in case of emergency, only. This picture illustrates an interesting adaptation in the body contour. The big "hump" in the shoulder region indicates that the body became an integrated part of the circulation system generated by the wings. Obviously, it con-

nects the bound vortices of the wings smoothly. If there is no gap in the circulation distribution along the wing span, no trailing vortices will be generated at the inner part of the wings. The body contributes to lift generation, and the induced drag will be minimized. Although systematic studies on scale effects in aerodynamic shape optimisation of birds are lacking, on my personal impression, the hump in the shoulder part becomes most pronounced in birds with high wing loading.

Engineers have has just started to utilise those principles in the design of modern fixed wing aircraft. But especially in civil aircraft design, there seems to be a large potential for further optimisation, and, possibly, some lessons can be learned from nature.

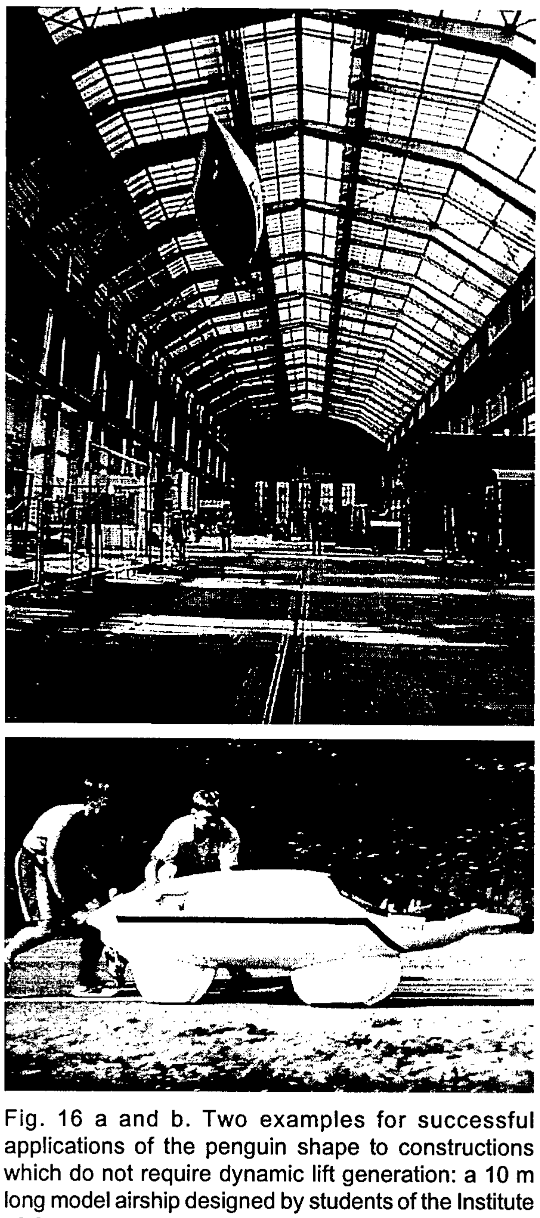


Fig. 16 a and b. Two examples for successful applications of the penguin shape to constructions which do not require dynamic lift generation: a 10 m long model airship designed by students of the Institute of Space and Aircraft Research, TU Berlin (a), and a human powered vehicle (b) constructed by students of the TH Hamburg in co-operation with the model lab of Daimler-Crysler. Both applications confirmed the excellent aerodynamic properties of the bionic shape in practice

Fig. 17. Giant Petrel (Macronectes giganteus) in flight. Please, pay attention to the contour of the body (photo: Bannasch)

3. Bionic Airfoil-Constructions

3.1 Feathers Help to Prevent Flow Separation

Same as in engineering, flight safety represents the strongest criterion for selection in flying animals as well. Considering, flow separation represents one of the major reasons for crashes in aviation, one may wonder how birds are able to manage crucial flight situations. Apart from the pilot's skill and favourable scale effects certainly involved, some explanation can be found also in the structure of the bird's flight apparatus. It is well known in ornithology that e.g. during the landing approach or in gusty winds, the feathers covering the upper surface of the bird wings may pop up. In analogy to the behaviour of wool threads often used in aerodynamics for flow visualisation, biologists interpreted the coverts in conjunction with the mechanoreceptors in the skin as a sensor system indicating flow detachment to the bird [39, 40]. However, in the thirties of the 20th century, the aircraft designer W. Liebe became puzzled by the idea that there might be some functional analogy to the boundary layer fences, he was working on. In 1938 he created an experiment in which a peace of leather was attached to the upper side of one wing of a fighter airplane, a Messerschmitt Me 109, to simulate bird feathers. He reported (pers. comm..) that the leather flap caused a dramatic asymmetry to the aerodynamic behaviour of the airplane by increasing the lift at the respective wing, especially at higher angles of attack. Since the pilot hat difficulties to handle the aircraft while landing, the experiment was considered to be too risky to be repeated again. 40 years later, Liebe explained his ideas in a journal article [41]. Separation starts from the trailing edge where the flow may become instable at a certain location along the span. Following the negative pressure gradient at the suction side, it spreads out towards the rear of the wing. As soon as the separation reaches the low pressure zone at the leading edge, the lift suddenly breaks down, the wing stalls. In birds, however, the reverse flow causes the light feathers to pop up, where after they act like a fence or brake preventing the separation of the flow to spread out any further. Considering that

flow separation is a three-dimensional effect and for the most part it starts as a local event, it seems to be an advantage of feathers that they can react locally by forming so called "reverse flow bags" just marking the endangered zone off, so that the flow over the other parts of the wing can be remained undisturbed preserving lift generation by the wing.

Liebe's ideas stimulated some rather tentative flight experiment conducted by a group of pilots in Aachen [42]. But this report gives only a short information that a movable narrow plastic strips was attached on a glider wing close to the trailing edge.

In 1995, a special research project on this issue was started by our Bionic Department together with three other research partners: The DLR Berlin, the Institute of Fluid Mechanics at the TU Berlin, and the STEMME Aircraft Company in Strausberg near Berlin [43-46]. Prior to this project, by chance of our Antarctic expedition, we could make detailed observations on the biological aspects involved. While some of us were working on penguins, another expedition member, Ingo Rechenberg, investigated the flight manoeuvres of the Skuas nesting near the colony. Using a telelens with fast autofocus, he could make hundreds of photographs documenting the dynamic behaviour of the wing feathers in any possible flight situation (see e.g. Fig. 18). Thus, we could gain a deep understanding on what happens on the bird wing in situ. These studies became extremely useful for the technical experiments carried out later on.

Fig. 18. Antarctic Skua in a landing approach (low speed, high angle of attack). The coverts of the right wing form a "reverse flow bag" restricting flow separation to a small, non crucial area close to the trailing edge (photo: Rechenberg)

To get maximum benefit from these observations, our group decided to concentrate on wind tunnel experiments simulating flow regimes close to those observed in nature, whereas the group of Dietrich Bechert (DLR) used to conduct studies on a section of an original STEMME airfoil in the large wind tunnel of the HFI in order to learn about the effects of movable flaps at flow conditions close to technical applications and to prepare a construction to be eventually tested on a STEMME S10 motor glider in real flight experiments.

The model wing, we used, was rectangular, span: 0,70 m, chord length: 0,20 m, A = 3,5) without endplates to allow for the development of tree-dimensional effects. A NACA 2412 profile was chosen since it shows a well pronounced decrease in lift beyond the critical angle of attack (solid lines in Fig. 19). The wind speed in front of our free-stream wind tunnel was adjusted to 10 m/s. Two electronic balances were used to measure the lift and drag force separately.

A large variety of materials and flap designs was tested to find the right properties, size and optimal attachment position to achieve the desired effect. The flaps could be easily changed. In the given flow regime a simple TESA-strip could be used to fix their leading edge to the model airfoil so that the flap could pivot on this line. From this first series of experiments, ilt turned out that a thin plastic material did the best job. Most important was to make the trailing edge flexible enough to be sensitive to the reverse flow. This facilitates the whole flap to pop up in time to prevent further disturbances. The flap must be flexible also in the spanwise direction, otherwise it may cause a dramatic increase in drag by disturbing the flow e.g. in the region close to the wing tip which (in a tree-dimensional case) is usually much more stable in view of separation.

An undesirable effect was, however, that the flaps became slightly raised, even under attached flow conditions. A typical engineering approach to fight the there from resulting drag penalty would be to lock the flap onto the airfoil surface in an appropriate way and to release it when necessary. But such an attempt would be in contradiction to our "bionic philosophy". Why birds do not need those mechanisms? To answer this question, W. Muller and G. Patone, who did most of the experiments, designed a series of additional investigations to learn more about bird feathers. They came up with a surprising result: the coverts are not airproof. They have tiny pores allowing a small air flow to penetrate through. This small "leakage" can be neglected when the feathers are exposed to a large volume stream as occurs in a separated flow regime. But it plays an important role to keep the coverts in the profile line under attached flow conditions. Considering the static pressure gradient in the chordwise direction on the upper surface of the airfoil, the leading edge of the feathers or flaps protrudes into the minimum pressure zone, whereas the trailing edge experiences a relatively higher static pressure. Since the trailing edge is open, the pressure beneath the flap equals to the static pressure at the downstream part of the airfoil. Due to the pressure difference between its lower and upper side, the flap becomes slightly lifted. In a porous flap, however, the static pressure at both sides becomes balanced. The implementation of this "trick" caused a substantial improvement of our constructions. Later, Bechert and his team have found out

that a similar effect can be achieved also by making the trailing edge of the flap jagged. This second method can be interpreted to mimic the serial arrangement of the coverts. It facilitates an exchange of pressure as well.

Eventually, in our small scale experiments, best results were achieved by a flap made from silk, using a few steel wires to keep it in shape in the chordwise direction but allowing a high degree of freedom in view of the flexibility in the spanwise direction (Fig. 19). By applying this construction, the critical angle of attack could shifted from initially 18 degrees to more than 40 degrees. As desired, this flap was very sensitive, popped up and reattached automatically, with a small hysteresis. The lift measurements show that apart from stall prevention, those self-activated flaps may serve also as high lift devices. Most interesting in this conjunction was, that, at least at the relatively small Reynolds numbers used in our experiments, such an effect can be achieved just by a tiny membrane. However, it must be large enough in size. As long as its trailing edge stays in contact with the outer flow (to be not "washed over" by the reverse flow), the position of this flap becomes self-stabilized.

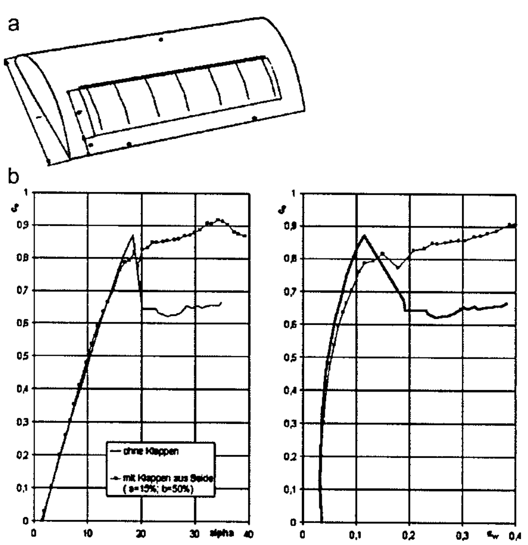


Fig. 19. Silk flap installed on a NACA 2412 airfoil (a), experimental data (b), solid line: without flap

Visualisation experiments using a smoke sonde showed that a large steady vortex is formed in front of the flap, whereas behind or underneath the flap, a zone of highly unsteady flow was observed (Fig. 20). Measurements on the static pressure distribution indicated further, that the steady vortex in front of the flap has to be considered as an integrated part of what is usually described as the bound vortex in wing theory. Although it is located on top of the profile, it makes a major contribution to the lift generated at that part of the wing. As this compensates for the decreased lift in the downstream part of the wing, a momentum shift must be evi-

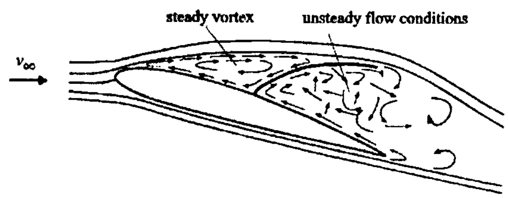


Fig. 20. Scheme of the flow pattern observed in smoke visualisation experiments. (PhD, G. Patone)

Fig. 21. Cross section of a bird wing (redrawn from [XX])

dent (unfortunately, those measurements were not considered in our experiments).

Considering the typical arrangement of feathers in a bird wing (Fig. 21) one becomes aware of the following aspects: 1. the coverts are considerably longer than the flap we used, 2. they are attached to the very rear part of the wing, and 3. birds possess several consecutive rows of coverts which overlap each other so that a smooth contour of the wing profile is formed. It results from the later that in function, that means when e.g. the caudal coverts pop up, the anterior coverts will be elevated as well. Consequently, the whole nose of the wing obtains another profile. It is possible that the formation of a free steady vortex on top of the profile (Fig. 20) was an effect of our simplified technical arrangement. However, experiments performed by the DLR team with more than one movable flap turned out to be tricky. We could gain just a small insight, and further research is required to deeper understand the highly sophisticated mechanisms of self-adapting wings developed in birds.

A major problem in transferring those mechanisms into engineering is that the aerodynamic forces increase drastically at larger dimensions. That's why the DLR team did not follow our "membrane theory". Another substantial limitation resulted from the fact that in the STEMME S10, laminar glider airfoils (Horst and Quast profile HQ 41) are used. In order to maintain the laminar effect over the first 70% of the chord length, Bechert and his team have designed comparatively small flaps having a length of about 12% of the airfoil chord length. The were attached to the airfoil so that their trailing edge was located slightly upstream of the trailing edge of the airfoil. In this arrangement, limiting strings had to be attached to the flaps to ensure that they do not tip over into the forward direction when exposed to the reverse flow. The beneficial effect of the flap was limited to its full opening. In the given arrangement, the lift increased by up to 10%. Beyond that point, a further increase of the angle of attack may not prevent the separation from jumping over, with the consequence that the effect of the movable flaps may

vanish. A consequent implementation of all these aspects would have required a completely new wing design. But even by the largely provisional set up tested at the STEMME S10 aircraft, remarkable positive effects could be achieved in real flight tests.

More detailed information on the experiments carried out by the DLR / HFI / STEMME can be found in [43, 44], for the studies conducted in our department see [45, 46].

In the given context, it might be worth mentioning also another promising approach. In his master thesis, one of our students, B. Goksel, applied the electro-aerodynamic effect to control separation and to enhance the lift production [47, 48]. In this experiment, Plexi glass end discs were attached to the rectangular airfoil to maintain the flow two-dimensional. A thin corona discharge wire (diameter 0,15 mm) was arranged in the spanwise direction in front of the conducting leading edge of a dielectric airfoil. Additional wire electrodes are located on the upper surface of the wing.

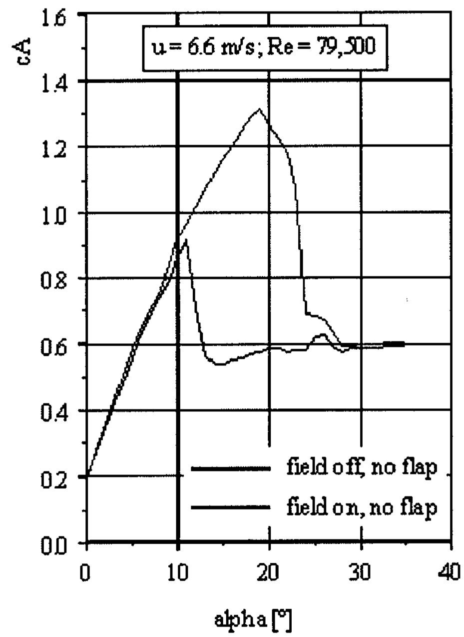


Fig. 22. Electro-aerodynamic separation control and super-circulation effect (low Reynolds number) [47]

When applying high voltage 16-17 kV with a corona current of max. 0,5 mA (non-lethal power range), the electrostatic field causes a weakly ionized air flow. The tangential ionic wind accelerates the boundary layer. As it contributes to the circulation, the bound vortex becomes strengthened, and the lift produced by the airfoil increases (Fig. 22). It should be noted, however, that in the given experimental set up, the ionic wind effect was limited to rather small Reynolds numbers. Nevertheless, in a certain range of supercritical angles of attack the separated flow could be fully reattached by switching the electrostatic field on. Further improvements are in preparation. It turned out that the active electro-aerodynamic lift and separation control and the passive movable flaps may work together.

3.2. Bionic wing tips and their potential for induced drag reduction

Aerodynamic lift generation by an airfoil with limited span unavoidably leads to the production of vortex sheet in the wake (Fig. 23), which rolls up to the so called tip vortices. These vortices induce a cross stream velocity field causing a backward force experienced by the airfoil. Apart from the work against friction and parasite drag, additional work is required to compensate also for the energy loss due to this induced force. In each of the concentrated trailing tip vortices, the circulation equals to the maximum circulation of the bound vortex. The total energy contained in the flow field induced by such a vortex system may vary since it depends also on the distance between the vortices.

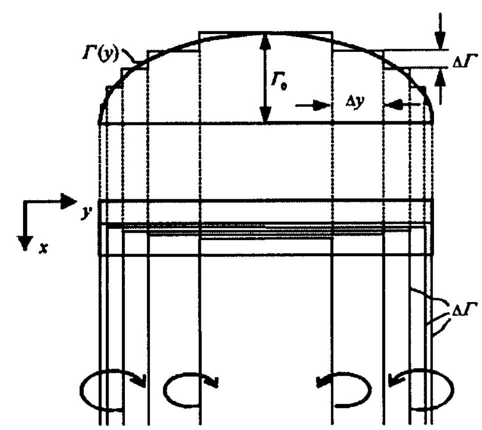


Fig. 23. Vortex model of a planar airfoil with finite span (redrawn after 49). Vorticity is shed from the trailing edge mainly in the wake of the tip region where the circulation distribution in the bound vortex shows the steepest gradient. At each side, the total circulation in the wake is equal to ?0, the maximum circulation of the bound vortex (the roll-up mechanism is not shown in this graph.)

The easiest and most effective measure to reduce the induced drag is to increase the wing span. This strategy is widely used in aircraft design (e.g. gliders) as well as biology (e.g. the Wandering Albatross). But often, the wing span becomes limited by other considerations (ground handling etc.). Similarly in nature, there are many environmental situations and functional restrictions qualifying shorter wings to be better applicable. So how did nature answer the induced drag problem in this case?

Most of the birds soaring over land (e.g. eagles, vultures, storks and kites) show char-acteristi-cally slotted wing-tips (Fig. 24). In response to aerodynamic forces acting on them during flight, the primaries (i.e. the feathers of the hand or, in technical terms, winglets) bend up and be-come staggered in height. Those multiple-winglet configurations are thought to re-duced the induced drag. Such effects are well known from other non

planar lifting-sys-tems in engineering, e.g. those described by Prandtl [50, 51]. In his pioneering studies, he has shown that in biplanes and multiple planes, the kinetic energy in the trailing vortex sheet, and hence the in-duced drag, can be reduced by the spatial spreading of the vorticity in the wake. How-ever, in multi-planes, this beneficial effect becomes somewhat counterbalanced by an increase of the friction drag. But most of the vorticity is shed from the tip region. There is no need for a non-planar arrangement in the inner part of the lift producing system [52]. In this respect, the multi-winglet configuration developed in birds can be seen as a synthesis of a multiple plane reducing the induced drag by spreading of the vorticity in the tip region [53, 54] and a planar wing keeping the friction drag low at least in the central part of the lift generating system [55].

Fig. 24. Black Vulture (Brazil) in soaring flight. (Photo: Rechenberg)

In practice, however, the construction of a multiple winglet configuration is rather com-plicated. Due to their complex aerodynamic interaction, the various parts must be carefully adjusted in order to obtain the desired effect in drag reduction [56]. To facilitate this, a wing was designed with slotted wing-tips which could be varied in respect of their vertical angle and their angle of attack. This was achieved by making the joining base out of lead. In wind tunnel experiments, the geometry of this wing (with five winglets at each end) could then be optimized by means of the Evolution Strategy [2]. In the course of the experiment conducted by M. Stache in our department [57, 58], a winglet configuration with a geometry very similar to that of soaring land birds has been evolved (Fig. 25a). In this configuration, the gliding ratio was improved by 11% compared to a planar wing of equal area and span (Fig. 25b). Numerical flow computations confirmed that the induced drag and also the total drag were lower than in a con-ven-tional mono-winglet wing. Theoretically, the effect can be enhanced by in-creasing the number of winglets, but the greater the number of winglets the more pro-nounced the interference between them and also the friction drag become. Eventually, the flow through that array becomes totally blocked.

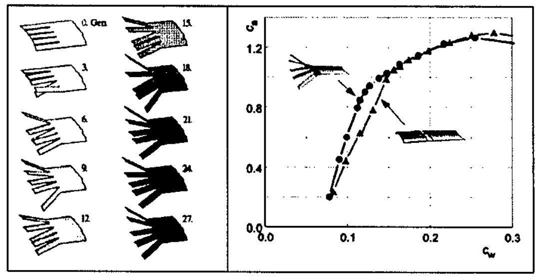


Fig. 25. a – Experimental optimization of a multiple winglet configuration, b – data of the initial and final wing tip v = 7 m/s, Re = 85 000, L = 3,9 (Experiments and graphs by M. Stache)

Because of these constrains as well as in an attempt to simplify the construction, a new wing configuration was developed. During numerical optimization of the vortex distribu-tion in the wake of a three-dimensional lift generating configuration, also by means of the Evolution Strategy, most of the vorticity concentrated along the vertical outlines of that field where a continuous vortex sheet was formed [55, 58]. When discussing the results of both optimization experiments in conjunction, M. Stache and I came to the idea [59] to totally re-move the inner part of the multi-winglet configuration and to develop, instead of that, the enveloping curve of the whole configuration as a lifting line (Fig. 26).

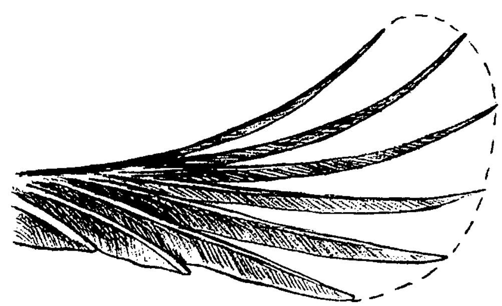


Fig. 26. Theoretically, the induced drag can be minimized by an infinite number of winglets. In this case, the tip vortices would form a continuous vortex sheet along the outline of this configuration. Certainly, such a configuration can not be built in practice. But a similar wake configuration may be achieved by a lifting line shaped like the enveloping curve and by an appropriate arrangement of the circulation distribution along that line

In practice, such a configuration can be achieved by making the now remaining upper and lower winglet broader so that the lift of the pla-nar base part of the wing fully splits up between the two branches. The ends of these branches must then be extended and bent in order to be connect-ed. In this way, a con-tinuous closed split-wing loop will be obtained. By adjusting the twist, camber and chord length along that configuration, an optimal vortex distribution (continuous sheet) in the wake can be achieved [55, 58, 59]. The arrows in Fig. 27a illustrate that at connecting point of the two branches, the lift gently switches from one to the

opposite surface, the circulation of the bound vortex changes its sign, the suction side converts into the pressure side and vice versa, like in a Moebius strip. It doesn't matter whether the circulation along the airfoil changes from Γ to 0 or from $0{,}5\Gamma$ to $-0{,}5\Gamma$, the vortex filaments induced in the wake rotate all in the same direction since their spin depends only on the local gradient in the bound vortex circulation, not on its absolute value.

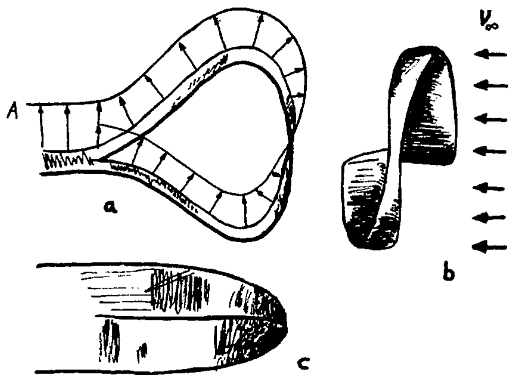


Fig. 27. Sketch of the bionic wing tip configuration "Split Wing Loop"; a – frontal view with lift distribution, b – side view, c – top view [59]

Apart from the reduction of the induced drag, also the drag penalty due to friction can be minimized. Compared to the initial multi winglet configuration, the total length of the trailing edge of the wing be-comes reduced. Keeping the central part of the wing planar allows to take advantage of the higher local Reynolds number (reduction of the local wall shear stress) in this area. Additionally, the chord length at the outer part of the loop can be reduced to the degree that the mechanical stability is still guar-anteed, but this refers only to the area in which the circulation changes its sign (Fig. 27b). Experi-mental investigations to verify the theoretical assumptions are in preparation.

Apart from the new aesthetic impression, this new design can probably be better handled than a wing with many winglets at its tip. Furthermore, it may help to reduce aerody-namic noise and to facilitate the dissipation of the tip vortices which represent a serious consideration e.g. for the starting and landing frequency, especially when huge aircraft become involved. A wide field of other applications (propellers, wind turbines, swords of sailing boats etc.) is conceivable.

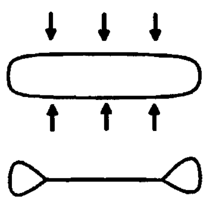


Fig. 28. A conceivable alternative methods, which may lead to the same principal construction is to take a box-wing or circular wing and squeeze the central part together to make it planar

Fig. 28 illustrates that a similar construction can be obtained also in other ways. If that, indeed, represents an optimum, let's say the top of the fitness hill, so one can imagine that it can be approached from various sides. And, there were other climbers as well. Soon after our bionic invention titled „Schlaufenformiger Quertriebskorper / Split-wing loop" [59]has been submitted to the patent office, we found out that before us, Luis Grazer, the former Boing Chief of aerodynamics, came from another side to a very similar solution, a construction, he called "Spiroid Wing Tip" [60]. Some minor disadvantages of the construction described in his patent could, obviously, be eliminated when a practical application was developed. Fig. 29 shows that Spiroids eventually applied to a Gulfstream II aircraft [www.aviationpartners.com] became more "organic". Thus, the mechanism called co-evolution in biology seems to work in engineering as well.

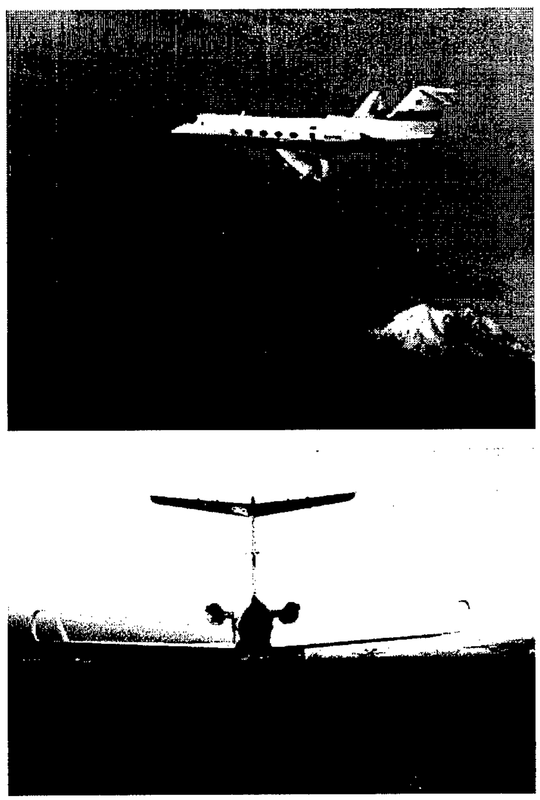


Fig. 29. Gulfstream II aircraft with Spiroid Wing Tips developed by Luis Grazer. (Photographs taken from the home page of the Aviation Partners, Inc.)

The home page of the Aviation Partners, Inc. informs that initial flight tests of the Spiroid concept on a G-II carried out in 1998 yielded a reduction of the cruise fuel consumption by more than 10%. The Spiroid eliminated concentrated wingtip vortices, which represent nearly half the induced drag generated during cruise. Vorticity is gradually shed from the trailing edge. No doubt, engineers may not need to study biology to find optimal structural solutions. However, this particular example shows that the various lines of development converge when ap-

proaching the optimum. Meanwhile, we have heard [J. Rayner, pers. comm.] that another construction called "Moebius Wing" has been developed in Russia, possibly even earlier. Unfortunately, we were not able to obtain a copy of that patent, as yet. So, it remains a mystery to us, what's behind.

4. Bionic Propeller

So far, only the fixed wing situation was considered. It is well known, however, that in a rotating airfoil, the problem of concentrated wing tip vortices becomes much more pronounced. In aircraft using propellers, the amount of power and therefore the overall performance of an airplane is often limited not by the engine but by the amount of power which can be converted to thrust within the limitation of propeller size, propeller efficiency and noise produced. All three factors are strongly related to the strength of the vortices generated at the tips of propeller blades. By obvious reasons, the propeller size is often limited in practice. The higher the power level relative to the propeller diameter the stronger the vortices, efficiency is sacrificed and noise levels are raised. With this respect, the performance can be improved by enclosing the propeller in a shroud. Shrouds tend to disperse the tip vortices, but the vortices reform at virtually full strength some distance downstream from the propeller plane, limiting the benefits of the shrouds. Structural weight, manufacturing costs and a frictional drag penalty are other consideration limiting a widespread commercial application of shrouds.

L. Grazer puzzled about this problem as well. He came up with a "Ring-Shrouded Propeller" in which the shroud is attached to the propeller bales and rotates with them [61]. The shroud was shaped to produce counter-vortices close to the locations where the propeller blades shed their tip vortices. The idea of this invention was that in each pair, the two opposite rotating vortices will eliminate each other, and that, in consequence, only minute vortices are shed from the trailing edges of the propeller blades and the shroud. A major disadvantage of this construction seems to be that complicated adjustments are required to adapt the shroud to variable loadings of the propeller, and the concept of vortex killing by a secondary system does not really convince me. One can consider a propeller simply as pump producing a momentum flux with vortices appearing as a side effect, ore one can use the vortex theory to calculate the flow field involved. Independently from what the researcher like to give the priority, both approaches must conclusively lead to the same result.

So, let's go back to the roots. In the flapping flight of birds, at least the down-stroke represents a nice analogy to a propeller, and there are many species using a considerably high wing beat frequency. As one can see in slow motion films, many of these birds own wings with deeply split primaries, obviously for the same reason discussed above for soaring bird. From this consideration, we have learned that the multiple winglet concept as well as the there from derived Split Wing Loop are general principles which do not depend on scale effects. Thus, we may have a chance to apply our bionic approach also to propellers, possibly with some modifications.

The Split Wing Loop concept was intriguing since it allows to split and bend the respective lifting lines in any appropriate way and to adjust the circulation distribution along that lines in order to distribute the vorticity in the wake so that least energy is lost. In this respect, an optimal solution for a propeller would be to envelop the stream downstream from the propeller plane in a continuous vortex sheet. Such a wake configuration would be similar to that formed close to the trailing edge downstream from a conventional shrouded propeller but without the respective disadvantages listed above. But how to achieve that?

Let's take a usual propeller with, let's say, four blades. In a somewhat simplified model, each of theses blades can be represented by a lifting line with a given circulation distribution. The solid line in Fig. 30 shows the optimal circulation distribution, A. Betz found for such a configuration [62].

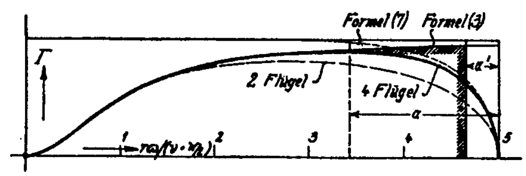


Fig. 30 Optimal circulation distribution at a propeller blade calculated by Betz [62]

Let each line split into two branches of about the same strength, with the split point at a position, let's say, where the circulation achieves its maximum. So, each of the two branches carries just half of the circulation of the basic part. In respect to the wake, this results in the formation of two smaller tip vortices, each having just half the strength of the initial large one. Now, we lengthen the branches of the lifting line with the consequence that the circulation distribution along these parts flattens out. In result, when looking at the wake again, vorticity is shed more gradually. But, as long as the respective vortex sheets have a free margin, they tend to roll up. The only measure to restrain them from reforming to a concentrated tip vortex is to connect the vortex sheets so that the velocities, the vortex filaments induce on each other, become balanced across the whole area. In contrast to the Split Wing Loop (or Spiroid) developed for fixed wing aircraft, in the propeller, we can take advantage from the serial arrangement of blades. Here, the desired configuration can be obtained in another way [63]. In each blade, with respect to the direction of rotation, we bed

one branch forward and the other one backward so that, respectively by their tips, the leading one connects to the trailing branch coming from the blade in front, and the second one connects to leading branch coming from the blade behind. Eventually, the outer part of the propeller will form a ring-like structure like shown in Fig. 31. Consequently, the vortex sheet shed from the trailing edge of this outer part forms a tube with a considerably thin wall. In the cross-section, it is not an ideal circle, but it is not far from that. All minute vortices in this tube rotate in the same direction. Their strength and special distribution can be optimized by adjusting the chord length, twist and camber along the close-looped outer part of the propeller. So, there is a real chance to eventually achieve a stable wake configuration.

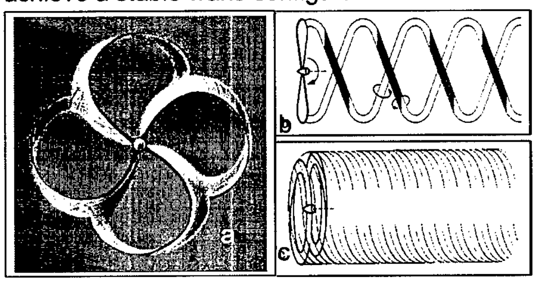


Fig. 31. Sketch of a "Bionic Ring Propeller" with 4 blades (a), while a usual propeller generates concentrated tip vortices (b), a continuous thin vortex sheet is shed from the trailing edge of the ring-like outer part of the Bionic Propeller (c)

The form of flow from the propeller sketched in Fig. 31c is known to involve minimum energy loss, i.e. maximum efficiency and also minimum noise generation for a given propeller loading [61]. Thereby, the small penalty in friction drag due to the increased overall length of the structure becomes more than compensated. Nevertheless, it may be appropriate to gradually reduce the chord in the middle of loop sections in a similar way as it was discussed for the Split Wing Loop.

Our first experiments with a Bionic Propeller made out of paper showed that close-looped, ring-like structure develops an enormous mechanical stability. Even the paper model was able to withstand considerably high loads. This can be advantageous also to keep the structural weight low. Moreover, it turned out that the construction is self-stabilizing, in a certain degree. The later property was investigated further by using a second model made from flexible plastic bands, which were flat (without profile) but twisted in an appropriate way. If one changes the angle of attack by turning the blades at their point of attachment to the hub, the whole configuration becomes twisted in itself. The twist angle declines gradually from the root towards the periphery. Certainly, this behavior can be influenced or steered by choosing the right stiffness distribution along that structure. Apart from that active manipulation, also some self-adjustment of the angles of attack, that means a certain passive adaptation to variable loads could be observed also in the second construction.

Even at this very preliminary stage of development, the Bionic Propeller (second construction) could well compete with a professionally designed propeller for model aircraft (Graupner) with similar design parameters. In our first wind tunnel tests, although the Bionic Propeller had no profile, it produced already twice as much thrust. The total efficiency suffered somewhat from some flow separation at the inner part, but, nevertheless, it was also a bit higher. There is no doubt, this concept works well, and with some optimization, it may find a wide range of practical applications. High efficient aircraft propellers, low noise ventilators, fans, exhausters, blowers, windmills, turbines etc. may benefit from this invention.

The Bionic Propeller can be adapted to work in water as well (Fig. 32). In liquid environments, also another interesting aspect comes up. Due to the reduced tip loading, probably, the highly undesired cavitation effect can be delayed. This would help to avoid material erosion and noise emission. Ships can be made ships faster. Bionik Propellers may also have a better "grip". So, their application can be useful to improves the maneuverability. We have just started to explore the interesting properties of this new construction. All what we have learned so far is very promising.

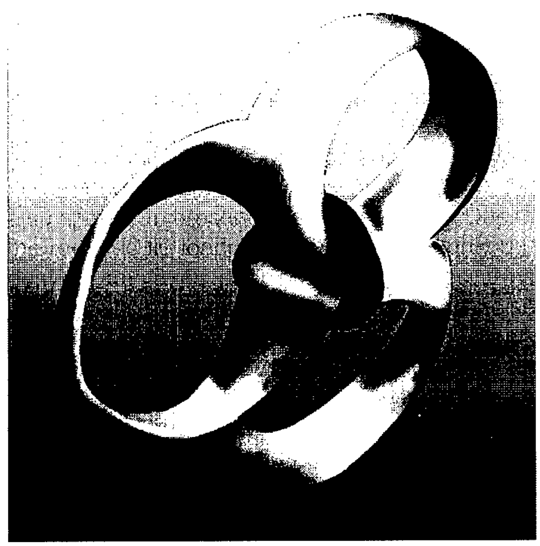


Fig. 32. Draft of a Bionic ship-propeller with 3 blades

The considerations made above apply to a single propeller. Although it is obvious to those skilled in propellers, it might be worth mentioning here as well that further improvements can be achieved when using e.g. a dual propeller arrangement with contra-rotation about a single axis. In such an arrangement, also the slipstream rotation can be eliminated. The same effect can also be achieved by keeping the e.g. the first propeller fixed (sta-

tor) and by arranging one or several Bionic Propellers in a line downstream. In such an assembly, propellers with different blade numbers can be used to avoid vibration due to interferences. And, in an optimal arrangement, the subsequent propellers may not have the same diameter. In a good design, their vortex systems should superimpose each other. Elimination of the slipstream rotation involves also the elimination of the vortex components rotating in the plane perpendicular to the main flow. This refers to the vortices shed from the inner parts of the blades close to the hub as well as to the vortex sheet forming the envelop of the wake. Eventually, the vortex system in the wake of such an assembly would consist of a thin vortex tube represented by a continuous sheet of minute vortices which rotate around circular lines. This vortex tube would enclose a linear jet-stream with constant velocity over the whole cross-section. Such a flow configuration would involve the absolute minimum energy loss, achievable. The aim of practical optimization is to approximate to this ideal as close as possible.

Finally, is should be noted also that a reduced fuel consumption, pollutants and noise emission, reduced total vorticity and faster dissipation of the vortices in the wake etc. are important considerations also in view of environmental protection. So, there may be some positive feed-back to nature as well.

5. Conclusions

This paper could give just some insights into a field of our current bionic research which might be relevant to modern aircraft design. Three major topics were addressed: Bionic fuselages providing maximum volume with minimum drag, some new concepts for bionic airfoil-constructions to improve flight stability and to reduce the induced drag, and the "Bionic Loop Propeller" increasing propulsion efficiency. Here, these elements were considered more or less separately from each other. Although there are many details which still have to be worked out, it seems to be obvious that modern aircraft design can profit from such bionic approaches. Eventually, we may become able also to combine those elements to develop complex functional units or even complete bionic systems. There is much we can learn from nature in that process. Nature does not provide "blueprints". But it helps to open our mind. Studies on biodiversity can facilitate a deeper and broader understanding of the fluid-dynamic phenomena.

No doubt, engineering may come to the right conclusions, on its own (e.g. Grazer's Spiroid Wing). But, many solutions do already exist in biology. Bionics may help to find and to take a shortcut in those developments. It does not per se offer solutions. Creative interdisciplinary work is required to figure the fundamentals out and to learn how to make use of these in practice. At a very early stage of development, some of the questions can be referred back to nature. At a more advanced stage, however, the technological application may loose any similarity with the biological example. Thus, on the first view, e.g. the Bionic Propeller seems to have nothing in common with a birds. Nevertheless, it represents the consequent implementation of a fundamental principle derived from a flapping bird wing, however, at a fairly abstract level. I am sure, when both sides, biologists as well as engineers, learn to think in this way, there will be a large benefit for all of us as well as for the environment. In this sense, there may be a good chance to combine our effort to develop more "organic" aircraft and other useful constructions in the near future.

6. Acknowledgement

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Dr. Boris A. PONOMARIOV

Date of birth: 1937

1961 – graduated from Moscow Aviation Institute,
speciality – "mechanical engineer of aviation engines"
1960–1961 – engineer at Institute #2480, Ministry of Aviation Industry
1961–1964 – post-graduate student at the Institute of Motors and Mechanics of the USSR Science Academy
1963 – present time – employee of Central Institute of Aviation Motors (CIAM)

Professional records:
1968 – Candidate of Science
1973 – Senior Researcher at CIAM
1974 – Senior Lecture of an educational institution
1984 – Doctor of Science
1987 – Professor of an educational institution
1969–1986 – Lecturer, Senior Lecturer, Professor at Moscow Institute of Engineers of Civil Aviation (a share-time employee)
1986–1987 – Professor at Moscow Higher Technical School (not in a permanent staff)
Lectures, training designing for students, works in training courses for engineers
1986 – present time – Head of "Low-thrust aviation engines" Department, CIAM

Author and co-author of more than 130 papers and reports, 3 monographs related to such problems as a choice of parameters and gasdynamics of turbines, designing and test development of engines for civil and military aviation, experimental investigations of GTEs and components.

Participant in ILA Air Shows in 1980, 1990, 1992, 1994, 1996, 1998

Field of interest:
- technological forecasting of aviation engine developments;
- development and improvement of calculation techniques and analysis of working processes of different engine configurations;
- theoretical and experimental investigations of engine characteristics and operability;
- expertise, final development, certification of civil and military engines, technical in-service support;
- program-methodological support of research works.

Good relations with Russian design bureaus, research institutes, manufacturing companies of civil and military aviation. Close cooperation with foreign R&D organizations and manufacturing companies.

STATE-OF-ART AND PROSPECTS OF RUSSIAN ENGINES FOR HELICOPTERS

In the early 1960s, first helicopter gas turbine engines (GTEs) were developed in the Soviet Union. These works were conducted by the design bureau headed by S.P. Izotov, Chief Designer. GTD-350 engine powered Mi-2 light helicopter and TV2-117 powered Mi-8 medium helicopter.

The GTD-350 engine manufacturing was launched in 1964 at "PZL" Co. in Zheshuv, Poland, and is under way up till now.

The TV2-117 engine manufacturing was organized at Perm's machine-building company where more than 23,000 engines have been built within 32 years. In 1997 the manufacturing was cancelled. However, these engines are still continuing their operation in Russia and abroad. In 1960s D-25V powerful engine was developed by the design bureau headed by P.A. Soloviov for Mi-6 heavy helicopter and for Mi-10 helicopter (otherwise known as a "flying crane") which was also manufactured at the Perm manufacturing facility. Totally, several hundred thousands were manufactured and the engine is in service up to now.

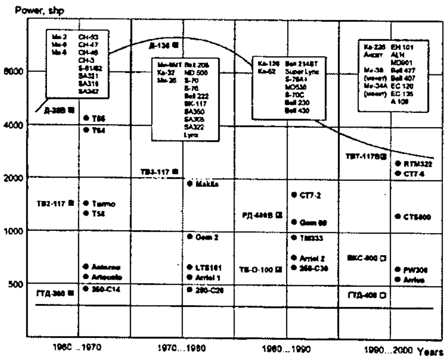
In 1970, the very promising 2200 s.h.p TV3-117 engine was developed by the design bureau headed by S.P. Izotov. Its initial manufacturing was organized at Zaporozhie manufacturing facility and is still in progress. Several engine modifications were designed within 30 years, that made possible to power different versions of military (combat, ship-born, transport) and civil (transport, patrol, water-bomber and special) helicopters – Mi-8MT, Mi-17, Mi-24, Mi-28, Ka-27, Ka-29, Ka-32, Ka-50, and Ka-52.

The engine performances were so perfect, that later, in the late 1990s, TV3-117VMA-SBM1 turboprop was developed on the basis of TV3-117VMA and installed in An-140 regional aircraft.

The D-136, which is the most powerful GTE in the world (11,500 take-off s.h.p.), was developed in 1970s in the design bureau headed by V.A. Lotariov. Its commercial production is still under way in Zaporozhie. The engine powers Mi-26 heavy transport helicopter, used in Russian military and civil aviation. These engines completely covered demands of Russia civil and military aviation ensured a parity, and even a superiority over potential enemies and competitors.

Statistical data related to Russian and foreign GTEs for civil helicopters developed within 1960–2000 are shown in Fig. 1. In view of take-off power of different engines, the following conclusions can be made. Firstly, the bottom line of take-off power is kept constant and equal to 350–400 h.p. It is the most advisable min. power of aviation GTE and piston engines could be more favourable below this level. Secondly, in the last few decades the upper

Engines for civil helicopters within the last 40 yesrs



line of take-off power moved down, that was due to a decrease in helicopter take-off weight keeping the same payload owing to introduction of new design concepts of flight vehicles, application of lightweight avionics, instrumentation, and composite materials.

However, at present helicopter GTEs are not produced in Russia for some reasons, although all former Soviet helicopter companies are located in Russia. Foreign manufactures of turboshaft engines took advantage of this situation and proposed their engines to Russian helicopter designers. In particular, Ansat, new Russian helicopter, is powered by PW206 turboshaft from Canada, Ka-226 uses Allison 250 and others, the Canadian PW127 is proposed for Mi-38 helicopter.

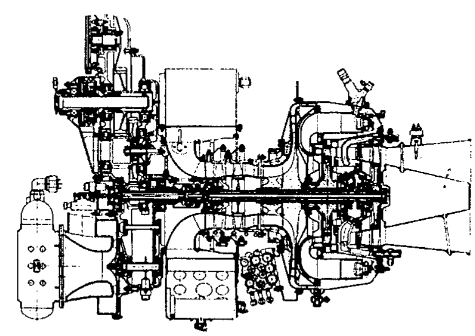
Being developed in 1960 – 1970s, turboshaft engines continue their operation in Russia and other countries and will be still in service for many years, though there is a keen interest in the development of new engines.

In mid-1980s, CIAM, in an effort to standardize turboshaft/turboprop engines, proposed a power-based classification consisting of 4 engine standard groups: I – 400 s.h.p. II – 800 s.h.p., III – 1600 s.h.p., IV – 3200 s.h.p. Furthermore, it is possible, if necessary, to develop GTEs of 2 additional groups: 0 – 250 s.h.p. and VI – 6000+ s.h.p. It was supposed that an engine in each standard group could be modified to increase its power by 15-25%. This classification was approved and standardized. It is worth noting that this classification is intended for both turboshafts and turboprops because these engines are very close in view of their thermodynamic cycles and structural configurations and are commonly used in helicopter and aircraft versions.

Aiming at future progress in aviation engines, CAIM completed a large scope of research works and studies resulted in technical and theoretical background (TTB) for the development of new engines. It was shown that a simple thermodynamic Brayton cycle could be used in future engines of the next generation and the most advisable scheme of a new engine should be provided with a single-shaft core, a power turbine with a front drive shaft and a built-in gearbox. The engine core could be either axial/centrifugal or centrifugal and equipped with a reverse-flow combustion chamber and a cooled turbine, but the power turbine should be uncooled. Its automatic control system is electronic-hydromechanical being integrated with an on-board control and diagnostic system (BCDS). As of the time of 1980s, the TTB was based on progressive methods of aerodynamic, heat and strength calculations supported by the experimental checks and verifications of the results at test facilities.

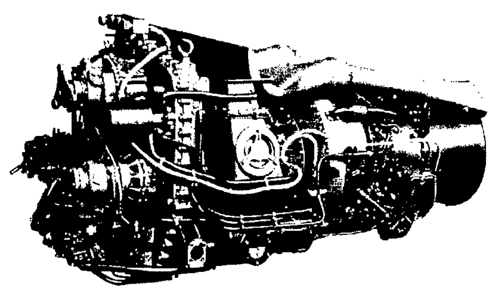
In line with this new approach Omsk Design Bureau headed by V.G. Kostogriz, General Designer, launched the development of 720-s.h.p. TV-O-100 turboshaft for Ka-126 helicopter. The development was accompanied by different bench tests; including tests in a thermal vacuum chamber (TVC), and flight tests, but in the early 1990s the project was shelved for well-known reasons. It should be recognized that the TV-O-100 (Fig.2) had a very promising structural configuration and high parameters of its working process. Also, there was a potential for further increase of the engine power to 800–850 s.h.p.

TV-O-100 turboshaft engine



"Rybinsk Motors" Co. is engaged in the test development of 1300-s.h.p. RD-600V turboshaft (Fig.3) for Ka-60 medium helicopter. Its core has a compact scheme and is provided with a four-stage axial/centrifugal compressor (3 ax. st.+ 1 centr. stage), a highly efficient reverse-flow combustion chamber and a two-stage cooled compressor turbine. Its two-stage uncooled power turbine drives the engine output shaft and ensures 6000 r.p.m. The engine is provided with dust and foreign object protective device with 2 ejection tubes. The automatic control system is composed of a main line (FADEC) and a

RD-600V turboshaft engine



back-up line (hydromechanics) and ensures the engine operability in all operating conditions, including start-ups, acceleration, emergency cut-off, etc.

The RD-600V has passed through extensive testing including tests in CIAM's TVC. On 24 December 1998, this engine-powered Ka-80 made its maiden flight and official flight tests were formally started in December 1999. These days' final checks and verifications of the RD-600V are under way and its final certification is scheduled for 2001.

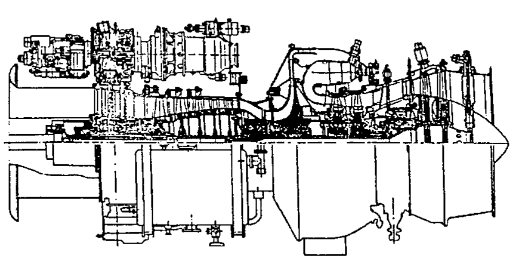
In parallel with this work "Rybinsk Motors" makes refinements of 1400-s.h.p.TVD-1500B turboprop having the same core with the RD-600V. The TVD-1500B is intended for An-38 regional aircraft.

Both the RD-600V and the TVD-1500B have very good prospects and could give a birth to a new family of turboshafs, turboprops and industrial GTEs.

Another very important engine in Russian aviation is 2500 s.h.p. TV7-117S turboprop designed by V.Yu Klimov's manufacturing facility headed by A.A. Sarkisov, General Designer. This engine has a type certificate, is in series production at "V.V. Chernyshov" Co. and powers Il-114 aircraft. Its "series-2" modification is in progress and will provide the increased take-off power (2800 s.h.p.) and time between overhauls (6000 hr). Moreover, another modification dubbed as TV7-117K and destined for lights ships was demonstrated at Moscow "MAKS'99" Air Show.

The helicopter modification of the engine is under designing in 2 versions: the TV7-117VK for available helicopters of "N.I.Kamov" Co. and the TV7-117VM (Fig.4) for Mil's Mi-38 helicopter. The final development of the engine versions is scheduled for the nearest future.

TV7-117VM turboshaft engine for Mi-8 helicopter



Thus, three out of four groups (II,III and IV) in CIAM's proposed classification found realization to some extent.

Up to now there were no Russian engines of the 1st group, despite of high demands, requests and proposals. In particular, "Granit" Design Bureau headed by S.R.Sarkisov, General Designer, proposed 2 modifications of its short-life MD-120 turbojet – 400-s.h.p. turboshaft and turboprop variants. The advantage of this project is the availability of the series baseline engine, although a field of application and, consequently, a structural layout and parameters of the baseline engine thermodynamic cycle determine the achievable level of new turboprops and turboshafs.

Recently, new proposals were received from other aviation companies related to the 1st group of GTEs but their realization calls for time and finances.

In the development of these helicopter engines customers, research institutes, design bureaus and manufacturing companies are striving to meet the following basic power (P) requirements: $\bar{P}_{emergency}$ = 100–120% of Ntake-off as a standard emergency mode for military aircrafts (MA) and $\bar{P}_{emergency}$ = 130–150% of $P_{take\text{-}off}$ – for civil aircrafts (CA); high power settings at cruise ($\bar{P}_{cruise}$ = 70% of $P_{take\text{-}off}$); operational self-sufficiency for MA (availability of an auxiliary GTE); IPS for CA and MA; provisions for accident-free operation in adverse environments (dust, sea salt, snow, etc.), long serviceability, easy repairability, technological effectiveness, some improvements in service life and such specific characteristics as specific power, SFC, specific weight, etc.).

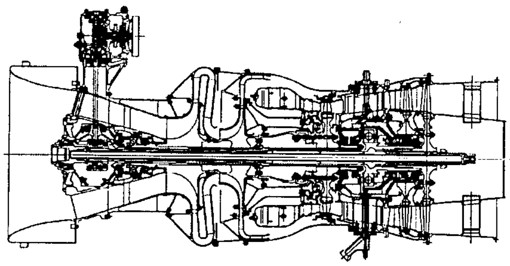
Aiming at these requirements, new helicopter engines are designed with high parameters of a thermodynamic cycle (PR_{max} = 15 and TIT_{max} = 1550K), decreased number of stages in the turbocompressor (total number is equal to 6–8) and small number of components (~3000), an electronic control system backed up by a hydromechanical system, and a modular structure of the engine as a whole.

However, such parameters as service life and reliability of the next generation engines should be considerably increased: TBO = 4,000–5,000 hr (8,000–10,000 cycles – for a combat helicopter and 6,000–7,500 cycles – for a military transport helicopter), total service hours = 12,000–15,000 hr (regarding cycles of unreplaceable critical components), MTBF= 20,000 hr – for a twin-engined helicopter and MTBF = 50,000 hr – for a single-engined helicopter, standard maintenance rate = 0.25–0.3 hr per flight hour, etc.

The realization of these requirements is only possible by involving up-to-date computational techniques, e.g. 3-D mathematical modeling, programs of service life prediction and the creation TTB of advanced designs and technologies. Among them are a highly efficient modular variable IPS, a single-shaft axial/centrifugal or a two-stage centrifugal compressor with PR = 18, a compact low emission combustion chamber, a cooled one-stage compressor turbine with a high expansion ratio, a highly efficient power turbine, an electronic control system integrated with BCDS of the engine and the flight vehicle with a decrease in total weight of all sub-assembly units by 20–30%. The engine should use not only new metal alloys by also composites and ceramics in such components as IPS, combustion liners, power turbine shafts, rolls of bearings, etc. (Fig. 5).

Simultaneous application of all these design solutions is impossible, but creation of TTB would allows to make a choice of the most favorable solutions which, in total, will determine a high technical level of a new turboshaft of the next genera-

Advanced turboshaft engine



tion in compliance with chosen requirements of the first priority.

However, the accumulated experience in engine operation and Russian economic situation transform typical requirements to helicopter GTEs. Advanced engines should have improved configurations and parameters. These projects implementation is based on advanced technologies, materials, computations and tests that could be achievable only with TTB which is a key task for research institutes and manufactures in Russian aviation industry. The task could be successfully solved only by close cooperation and collaboration.